IAEA-SM-329/24

INDUSTRIAL EFFLUENT DISCHARGES IN COASTAL WATERS: OPEN AND CONFINED BODIES

R.M. MOREIRA, V.L. BONTEMPO, A.M.F. PINTO
Nuclear Energy Development Center (CDTN),
National Nuclear Energy Commission (CNEN),
Belo Horizonte,
Brazil

Abstract

INDUSTRIAL EFFLUENT DISCHARGES IN COASTAL WATERS: OPEN AND CONFINED BODIES.

Radionuclides have long been in use for various measurements of coastal environment contamination. As to effluent disposal impact evaluation, its proper utilization depends on the discharge type as well as on characteristics of the receiving system. Industrial effluents, even at smaller flow rates, may be more deleterious than domestic wastewaters. Besides, their degrading effect will increase as one passes from open to confined waters; estuaries are the most sensitive coastal ecosystems. Industrial effluents also differ from wastewaters in that they may eventually be denser than sea water and, not infrequently, laden with particulates. In such circumstances, multiple tracers are instrumental. In any case, tracer measurements should always be backed by hydrological observations, often in conjunction with physicochemical and biological surveys. Only then will tracers be able to deploy their full potential. However, radiotracers may not be very effective in very dynamic systems such as estuaries. In these cases, natural tracers, when properly used, may assist or even substitute artificial ones. Salinity is the most obvious tracer of this type. The paper briefly describes some of the work performed in Brazil, each case dealing with a special situation.

1. INTRODUCTION

Industrial effluents are usually discharged in smaller quantities than domestic wastewaters but, on the other hand, are much more multifarious, toxic and refractory in the environment. The typology of receiving water bodies is another crucial parameter defining the disposal problem. This paper comments on some work performed in different situations in Brazilian waters.

Disposal in open water bodies is illustrated for two quite different effluents. One is solid waste (gypsum); in addition to the transport mechanisms during the dispersive settling phase, the behaviour of the settled insoluble residue at the ocean bottom had also to be accounted for. Laboratory and modelling work helped to complete the impact evaluation. In another open water disposal situation, the recirculation of cooling water from a power plant was considered. Now, one has to do with a buoyant effluent; nonetheless, sediment transport problems also intervene inasmuch as intake and outfall works will interfere with, and will possibly be hampered by, sediment transport.

Oil production and transport may give rise to a wide range of environmental impacts on coastal waters. Spills or intermittent discharges involve concentrated effluents; however, their tracer simulation can be carried out by well established methods [1]. Continuous discharges entailing larger quantities of less concentrated effluents occur in units such as oil terminals. The problem here is their location: usually in the calm waters of channels or bays, frequently heavily affected by urban or harbour areas situated in the neighbourhood. In the example given here an assessment of the prevailing conditions had to be made by monitoring both the effluent and the receiving water body. This illustrates the need for complementary physicochemical (or biological) measurements.

Contamination from oil production and by-product processing may threaten the delicate equilibria in estuarine systems. In small estuaries, radiotracers can be efficiently applied to define hydrodynamic and mixing capabilities. However, in medium to large systems the tracer cloud is literally exploded during flow reversal episodes. In such cases natural tracers may be helpful.

2. DISCHARGES IN OPEN WATERS

Phosphoric acid plants are prolific gypsum generators, accumulating huge piles of solids as well as creating environmental havoc. This impure gypsum is about 90% soluble in sea water, being contaminated with fluorine, low pH heavy metals and much more. Since these plants are frequently located near the coast, the idea of disposal in the sea through outfall or dumping is natural. Obviously, extensive impact assessment measurements have to be carried out, including hydrological, chemical and biological surveys. In these studies, radiotracers can be useful at two stages of the ensuing processes: turbulent dispersal and settled residue behaviour.

Such a study was performed for a planned outfall (1600 $m^3 \cdot h^{-1}$ total liquid flow rate, 1600 $t \cdot d^{-1}$ solid $CaSO_4$) at Imbituba, at the southern coast of Brazil. Obliquely ascending dense jets were to be sped upwards from the outfall ports near the bottom, attain an apex and fall down after a while. It was calculated that the residence time of the particulates in this arched path is long enough for the gypsum to get dissolved, leaving behind the siliceous insoluble fraction of about the same density as the sandy bottom sediment, but somewhat finer. The jets are energetic enough to achieve the required dilution in the rising stage, thus equating its density with that of sea water at half depth. Further spreading plus dilution by turbulent and shear mechanisms in the far field can be evaluated by the classical tracer methodology coupled to dispersion models [1, 2]. Instantaneous injections of the tracer (^{82}Br) create radioactivity clouds which are successively scanned and numerically integrated to generate the plume which would correspond to the continuous discharge mode. Dispersion parameters are evaluated by model fitting (inverse problem); non-linear search algorithms are required to cope with this task. This is no novelty, but for this particular effluent the dispersion coefficients were also important in predicting the spread of the settling non-solubles. This was accomplished by an advection–dispersion model [3], which can also be most useful in dredge spoil modelling. It assumes a Gaussian concentration distribution, which for the particle fallout rate at position (x, y, z_b) yields:

$$E = \frac{1}{4\pi\sigma_x\sigma_y\sqrt{\pi D_z t}}\left(\frac{z_0 - z_b + wt}{2t}\right)$$

$$\times \exp\left\{-\frac{(x - x_0)^2}{2\sigma_x^2} - \frac{(y - y_0)^2}{2\sigma_y^2} - \frac{[z_0 - z_b - wt]^2}{4D_z^t}\right\} \qquad (1)$$

where (x_0, y_0, z_0) are the initial co-ordinates, z_b is the depth, w is the fall velocity, σ_x and σ_y are the standard deviations, and $D_z = (1/2)(d\sigma_z^2/dt)$ is the dispersion coefficient at the vertical axis. The last three parameters are determined from tracer measurements. The impact at the ocean bottom can be evaluated by integrating in time, $R_w = \int E\,dt$, and converting the deposition rate R_w into the mound height growth rate R_z ($cm \cdot a^{-1}$):

$$R_z = \frac{R_w}{(1 - \epsilon)\rho} \qquad (2)$$

where ϵ is the void deposit ratio and ρ the particle density, both determined in laboratory tests. Isogrowth curves computed in this way exhibit the pattern shown in Fig. 1.

The above calculation, complemented by hydraulic assessments, informs on the possibility of the outfall being buried by its own refuse. However, once settled the particles do not stay there forever. Therefore, another concern was the definition and the quantification of the movement of the particles on the sea-bed, with their impact and eventual return to the shore. This could be accomplished by using labelled (^{189}Ir, $t_{1/2}$ = 74 d) ground glass as tracer, with the same size distribution as for the non-solubles. The tracer movement could be followed during one summer and winter and disclosed mild offshore drift (the cloud centre of gravity moved by 45 m), together with resuspension and/or burial of the particles.

Large heated water flows from the secondary cooling system of nuclear power plants (NPPs) are discharged into the ocean. Being warmer than the ambient water they will float, just as urban wastewater does; but since they are so bulky, they have to be discharged through channels directly at the ocean surface and are subjected to

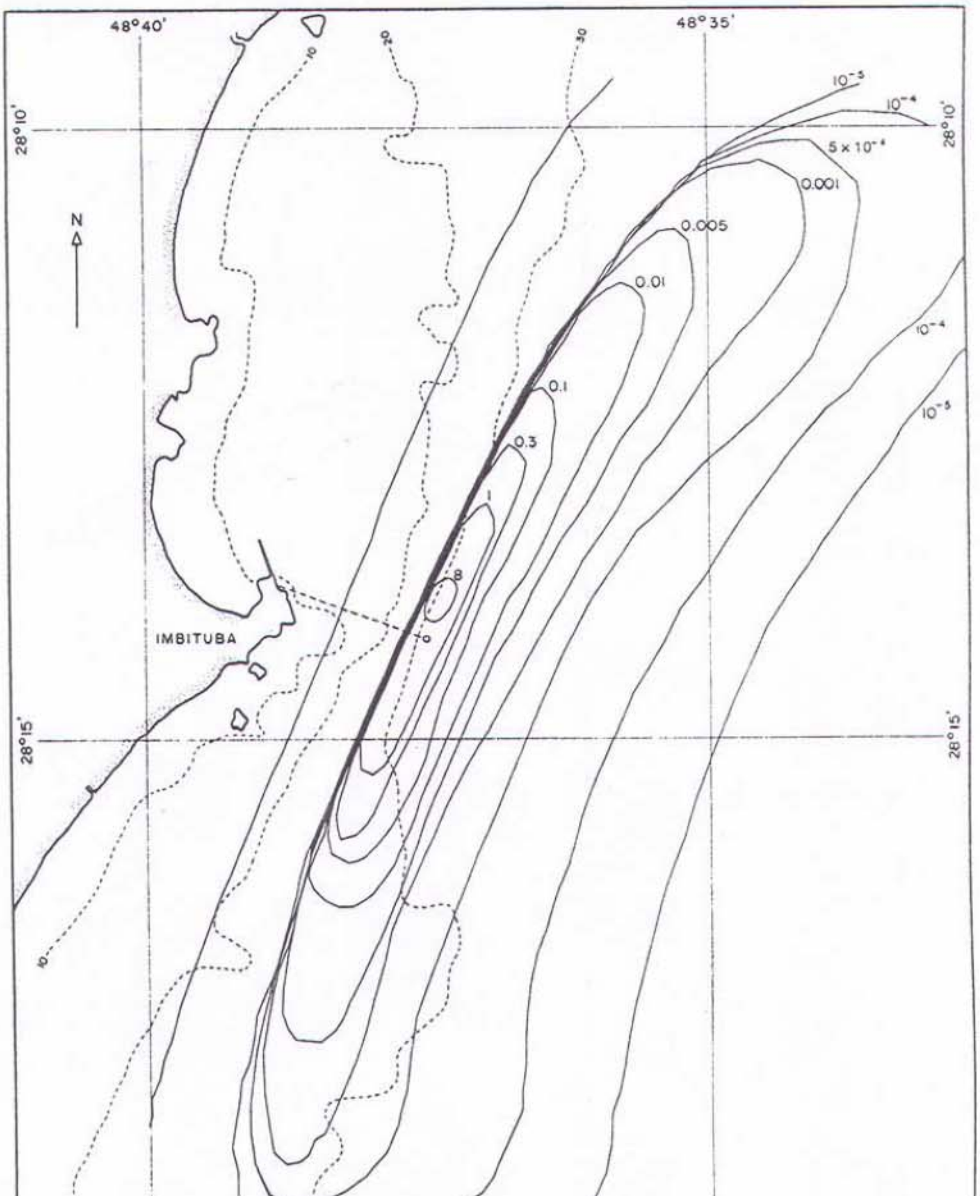

FIG. 1. Predicted growth rate distribution of non-soluble gypsum particle deposit over the ocean bottom at Imbituba ($cm \cdot a^{-1}$).

complicated boundary interactions. Besides damaging the biota, heated water may recirculate to the intake site and impair the plant efficiency. The site for a planned NPP (cooling water flow rate $Q = 80\ m^3 \cdot s^{-1}$ per NPP; temperature rise $\Delta T = 7.5°C$) at Iguape, at the southeastern coast of Brazil, was studied for over two years. Some tracer runs were performed for dispersion evaluation, but they had a limited scope as statistical requirements would overburden the working team and raise costs. Therefore, in addition to extensive hydrological recording, ancillary tracers such as drift cards were used. The data thus gathered were fed into mathematical models that estimate the chances of recirculation and the comparative performances of outfall designs.

Sediment tracer measurements (^{192}Ir labelled ground glass) were also significant in this connection since both intake and outfall structures would interfere with, and be hampered by, sediment transport. The tracer tests were performed hand in hand with hydraulic surveys and a thorough characterization of the bottom sediment. The tracer balance method devised by Courtois and Sauzay quantified the transport characteristics of bottom [4] sediment off the surf zone. It amounted to $150\ kg \cdot m^{-1} \cdot d^{-1}$, within 700 and 1400 m offshore during summer. These data were correlated with the hydrodynamic forcing functions, especially wave action. During winter the radiotracer method was hindered by the quite energetic sea conditions which dissipated the tracer cloud. Transport along the coast (about $500\ 000\ m^3 \cdot a^{-1}$) was estimated on the basis of local and neighbouring wave climates.

One most useful piece of information was obtained from surveying the background activity of the bottom sediment. Fine particles exhibit higher radioactivity levels than coarser ones, owing to their distinctive scavenging action. Moreover, wave action sorts the fine fractions seawards and the coarse fractions shorewards. The limiting line between high and low background counts was observed to drift back and forth some 900 m between summer and winter, remaining nearly parallel to the coast line. Figure 2 depicts the state of affairs. This finding emphatically confirmed the frontal sediment transport pattern, onshore in summer and offshore in winter; furthermore, it supported and enhanced the scope of the tests with artificial tracers (which were defective in winter).

3. DISCHARGES IN CONFINED WATERS

A typical case is the São Sebastião oil terminal, which serves the São Paulo region: it is the country's largest terminal and is sited inside a strait, right in the middle of one of the most highly praised places in Brazil. Oil spills from ships and discharges from land based activities were recurrent events so that a waste treatment system terminating in an outfall was devised. This is an instance of reclamation of a body of water that had been under strain for some years. Hence the obvious tracers

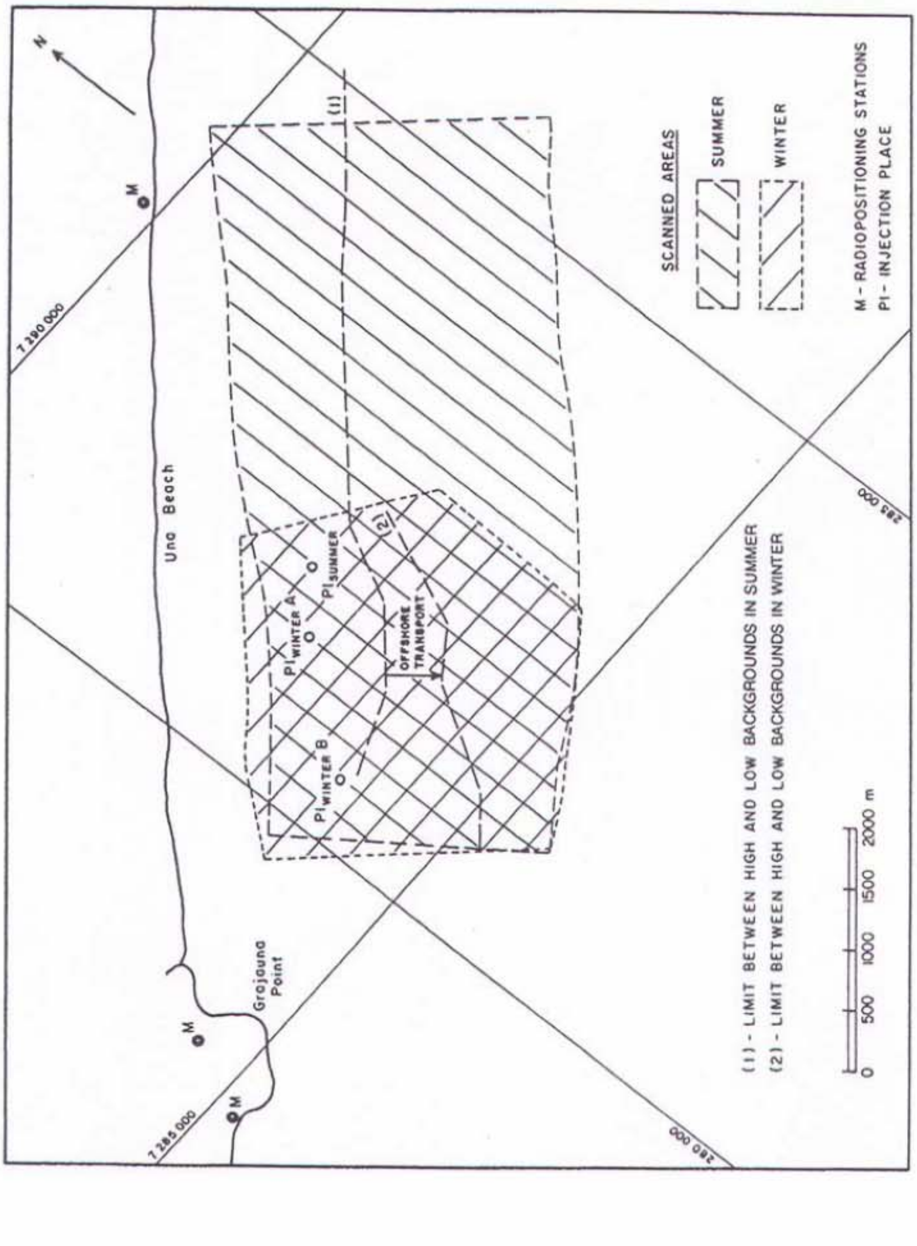

FIG. 2. Shifting of the natural radioactivity level of bottom sediment at Iguape.

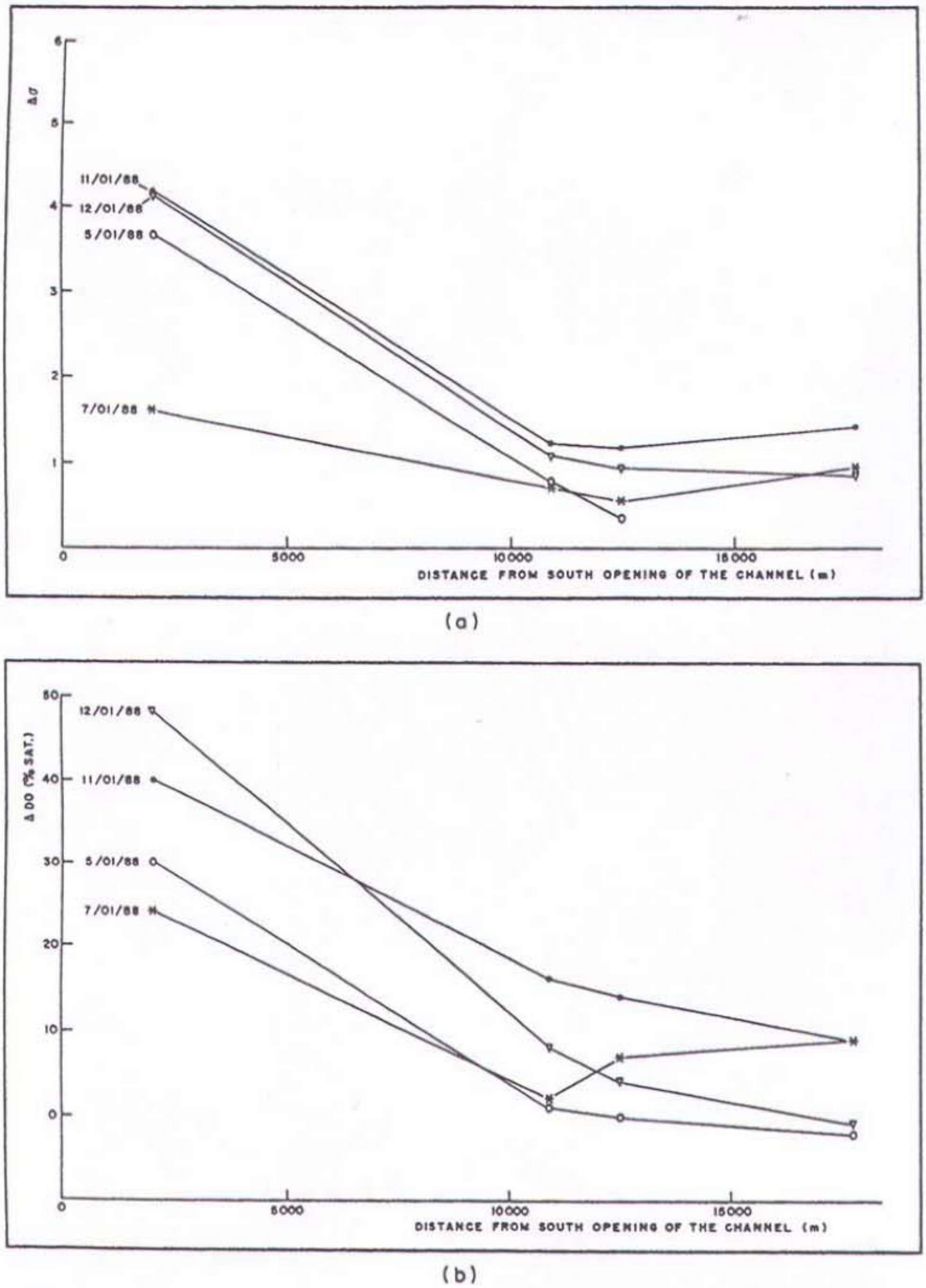

FIG. 3. Distribution of vertical gradients along São Sebastião channel: (a) salinity (σ); (b) dissolved oxygen (DO).

in this case were the discarded contaminants themselves, together with water quality indicators. Artificial tracers were left to rate the performance of the treatment units.

The representative parameters surveyed were: pH, temperature, water density, suspended and settleable solids, turbidity, oil and grease, biological oxygen demand on five days (BOD_5), phenols, NH_3 nitrogen, Cl^-, and S^{2-}. The procedure lasted one summer and one winter. Samples were collected along the channel at different depths. Basic hydrological information was available from the terminal authorities. Even though covering a minimum acceptable time period (schedules and budgets are always tight), the implied logistics were burdensome as analyses called for qualified laboratories and minimal waiting time. Anyway, the results allowed estimates to be made of the present contamination and its spatial and temporal distributions and provided the database for the outfall design.

Stratification being common in confined water bodies draining humid basins, the outfall jet would suffer the interference of variable density profiles in the water column. A survey and statistical analysis of previous density records had to be carried out. Within certain bounds, all above mentioned parameters can be regarded as tracers; in particular, they back up the vertical salinity profiles and evince their effect on contaminant segregation. Figure 3 shows some of the measured vertical gradients alongside the channel; here, $\Delta C = C_{surface} - C_{bottom}$, C being a generic parameter. Longitudinal concentration profiles at various depths are directly calculated from such sampling schemes. As will be shown later, longitudinal profiles can be used to give rough estimates of the dispersion parameters, besides pointing out the more heavily affected areas.

Estuaries are a very special kind of confined water environment, comprising highly productive but vulnerable processes. In the State of Sergipe, in northeast Brazil, there are two estuaries less than fifty kilometres apart. One of them, the Japaratuba River, is quite small; but it runs through one of the largest oil production fields in the country. The other, the Sergipe River, is medium sized and has attracted process industries fed by the neighbouring petroleum.

A field study has been conducted to ascertain the diluting capacity of the Sergipe River with regard to the effluents of a urea plant (main contaminants: ammonia and chromium). In a pilot test, ca. 1 Ci (3.7×10^{10} Bq) of ^{82}Br was injected into the river, and the tracer cloud was trailed for a couple of kilometres. Then, at a turn of the river, contact was suddenly lost. It took some time to realize that the cloud had been utterly exploded by a tidal flow reversal with its attendant powerful shearing action. This event sufficed to convince people that artificial tracers would not work in an estuary of this size. Nevertheless, a natural tracer was at hand: the shifting NaCl concentration profile resulting from salinity intrusion in estuaries, which amounts to a tracer step impulse at the estuary mouth.

Briefly, the concentration distribution $C(x, t)$ of a contaminant continuously fed into the estuary at point $x = 0$ and time $t = 0$, with concentration C_0 in the effluent, is given by the solution of the one dimensional dispersion equation [5]:

$$\frac{C}{C_0} = \int_0^t \frac{U_f}{\sqrt{4\pi D\ (t - \tau)}}$$

$$\times \exp\left\{\frac{-\left[x - U_f\ (t - \tau) + \dfrac{U_T}{\sigma}\ (\cos \sigma t - \cos \sigma\tau)\right]^2}{4\ D\ (t - \tau)} - K_c\ (t - \tau)\right\} d\tau \tag{3}$$

where the advective velocity, $U = U_f + U_T \sin(t - \delta)$, takes into account the oscillatory tidal motion in the estuary. U_f is the velocity component due to upland river flow, U_T is the maximum value of the tidal velocity, σ is the frequency of the tide and δ is the phase shift, all of which can be measured by the usual hydraulic methods. K_c is the disappearance rate for non-conservative components, determined in laboratory tests. As $t \rightarrow \infty$ downstream from the injection point, $C \rightarrow C_0$, where C_0 is the ratio of the effluent and landwater flow rates. D is the longitudinal dispersion coefficient, which has to be estimated by tracer techniques. Harleman and Thatcher [6] have shown that

$$D(x, t) = K \left| \frac{\partial \bar{s}}{\partial \bar{x}} \right| + D_T \tag{4}$$

where K is a parameter indicating the degree of stratification; $\bar{s} = s/s_0$ is the salinity at (x, t) normalized by that at the mouth of the estuary; $\bar{x} = x/L$, L being the length of the estuary; D_T is a Taylor type dispersion coefficient:

$$D_T = \frac{20\sqrt{g}}{c}\ R_h U \tag{5}$$

where g is the acceleration due to gravity, c the Chezy coefficient and R_h the hydraulic radius of the conveyance area.

Thus, averaged salinity records at various sections alongside the estuary can provide the much needed dispersion parameter. Numerical calculations of C(x, t) with the above methodology indicate the spread of discharged components away from the outfall location. One such calculation is shown in Fig. 4 for ammonia during the dry season ($D = 105\ m^{-2} \cdot s^{-1}$, $K_c = 0.1\ d^{-1}$, $U_f = 0.002\ m \cdot s^{-1}$). Contaminant distributions are shown for high water slack (HWS) and low water slack (LWS) episodes bracketing the whole range of concentration shift during a tidal cycle.

The case of the Japaratuba estuary was akin to the São Sebastião channel in that a system contaminated at a number of discharge points was to be recovered. The effluents from several oil–water separators were to undergo polishing at a central collection station before disposal. However, NaCl would not be eliminated and some

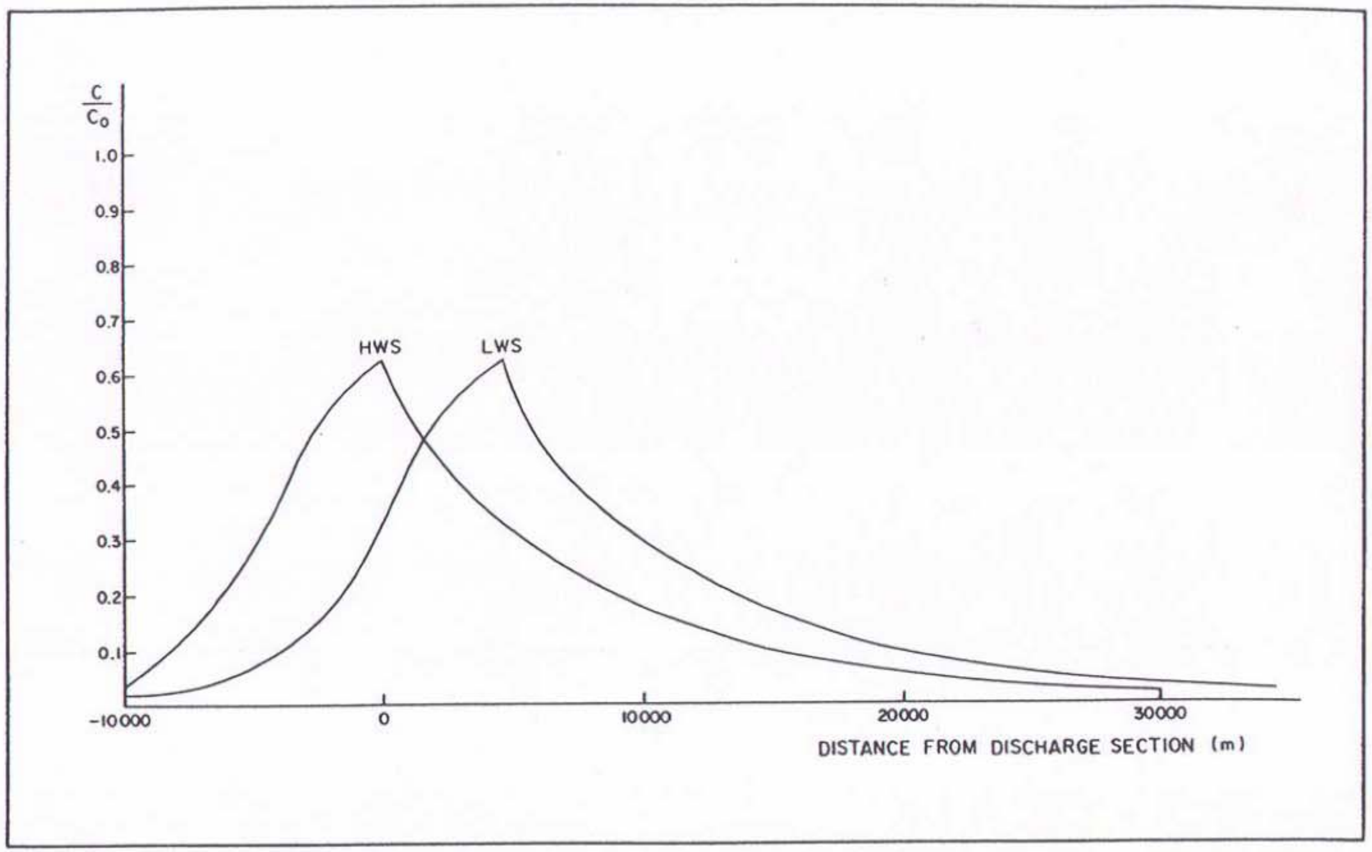

FIG. 4. Calculated ammonia concentration distribution along the Sergipe river during the dry season. HWS stands for high water slack, LWS for low water slack.

of the briny production waters exhibited salinity indexes well over 100 ppt. One scheme contemplated staged discharges along the brackish reach of the estuary upstream the final mangrove reach. The distribution of conservative components such as salt can also be calculated from Eq. (3). The shape of the distribution is analogous to that shown in Fig. 4, except that the downstream branch of the concentration distribution levels off since $K_c = 0$. The dispersion coefficient, also estimated from concentration profiles, defines the rate of raise of the excess salinity upstream each diffuser section (the raising branch in Fig. 4). This not only avoided a burst of brine into the estuary but also allowed optimization of the discharge dosage.

4. CONCLUSIONS

It is a pity that artificial radiotracers have not been more often used for in situ studies of surface waters. As a result of too severe legislation and unjustified prejudices, this segment of radiotracer engineering is almost at a standstill. Outfalls of any kind are just as controversial as radioactivity; their conjunction in the same undertaking, effective as it may be, is hard to sell. It is proposed that radiotracer work should be complemented by natural tracer measurements and other non-nuclear techniques, even when they are a must (otherwise, they should obviously be deferred). The cases discussed above try to illustrate this symbiosis: the radioactive tool can be made more palatable, and it is in this case that its full potential can be made use of. Natural tracers obviate safety questions, but it is a misconception that they are more economical. In situ detection of radiotracers is much easier, accurate and less costly than sampling and analysis work (salinity and some other in situ measurable parameters are exceptions, although less sensitive).

REFERENCES

[1] HARREMOES, P., Theoretical Treatment of Data on Turbulent Dispersion Related to Disposal of Industrial Waste, Rep. for Research Contract No. 402/RB, The Danish Isotope Centre, Copenhagen (1967).

[2] CSANADY, G.T., Turbulent Diffusion in the Environment, Reidel, Dordrecht (1980) 248 pp.

[3] KOH, R.C.Y., Initial sedimentation of waste particulates discharged from ocean outfalls, Environ. Sci. Technol. **16** 11 (1982) 757.

[4] COURTOIS, G., SAUZAY, G., Les méthodes de bilan des taux de comptage des traceurs radioactifs appliquées à la mesure des débits massiques de charriage, La Houille Blanche **3** (1966) 279.

[5] HARLEMAN, D.R.F., HOLLEY, E.R. Jr., HUBER, W.C., "Interpretation of water pollution data from tidal estuary models", Water Pollution Research (Proc. 3rd Int. Conf. Munich, 1966), Water Pollution Control Federation, Washington, DC (1966) 1.

[6] HARLEMAN, D.R.F., THATCHER, M.L., Longitudinal dispersion and unsteady salinity intrusion in estuaries, La Houille Blanche **1/2** (1974) 25.