FLUID-MECHANICS ASPECTS IN THE DESIGN OF SEWAGE OUTFALLS INTO THE SEA

by

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Sewage outfalls into the sea have much in common with chimneys for emissions into the atmosphere: both are intended to release pollutants in such a way that they are rapidly diffused and reduced to harmless concentrations. Chimney design aims at restricting the concentrations of pollutants near the ground to a tolerable level whilst, in outfalls, the aim is to afford the upper strata of water and the coastal regions in particular the maximum possible protection against pollution. Yet an essential difference lies in the fact that the atmosphere into which chimneys discharge extends upwards for large distances and, generally speaking, is subject to a high degree of vertical mixing while the coastal waters into which waste is released are comparatively shallow.

Waste outfalls and chimneys can have only a localized influence upon the reduction of concentrations of pollutants. At any great distance of discharge, it hardly matters what method is used to release pollutants. The sole decisive factor is how quickly they are decomposed by physical, chemical and biological processes. The continual release of substances which do not decompose is bound to cause an increase in the concentration. No discharge structure, however well designed, can remedy this. With decomposable substances this increase does not occur! Hence sea outfalls are acceptable for the harmless removal of pollutants such as domestic sewage but for non-decomposable substances they are just as unsuitable as any other form of dispersion.

Waste within the hydrological transport system

None of us would deny that the sea with all its forms of life must be protected against the detrimental consequences of human activities. On the other hand, we cannot avoid the problem of what to do with the waste products of human society. A fresh approach to this question shows that, with careful planning, a number of waste substances can be discharged into the sea without causing ecological damage or impairing human exploitive activities. A crucial factor is that the majority of so-called "pollutants" actually exist in the water under natural conditions and so we can refer to pollution only when a certain level of concentration is reached which exceeds "natural" tolerances.

Yet only those substances which are decomposed comparatively quickly by physical or chemico-biological processes are suitable for diffusion or "dilution" in the environment. We must make a clear distinction between these and a number of non-decomposable or very slowly decomposable substances which are not found in the natural environment and against which the ecosystem has no defence mechanisms. These substances – such as DDT, chlorinated hydrocarbons or radioactive waste – may have an injurious impact on the ecological system and must therefore either be rendered harmless at source or be stored in a suitable manner. In other words, they must be isolated from the natural environment. In contrast, it makes good sense to release other waste matter into the seas when action is taken to ensure that it will be dispersed as quickly as possible and reduced to concentrations in accord with natural levels.

Pollutants are transported in the environment mainly by natural processes. Various natural constituents of water, such as salts and sediments plus – in recent years – waste products from human activities, are constantly being released into the sea in one form or another as part of the hydrological cycle (Fig. 1). The evaporation, rainfall and drainage of the hydrological cycle make it an efficient transport system from land to sea which mankind has been exploiting since history began. So, taking a very broad view, the sea

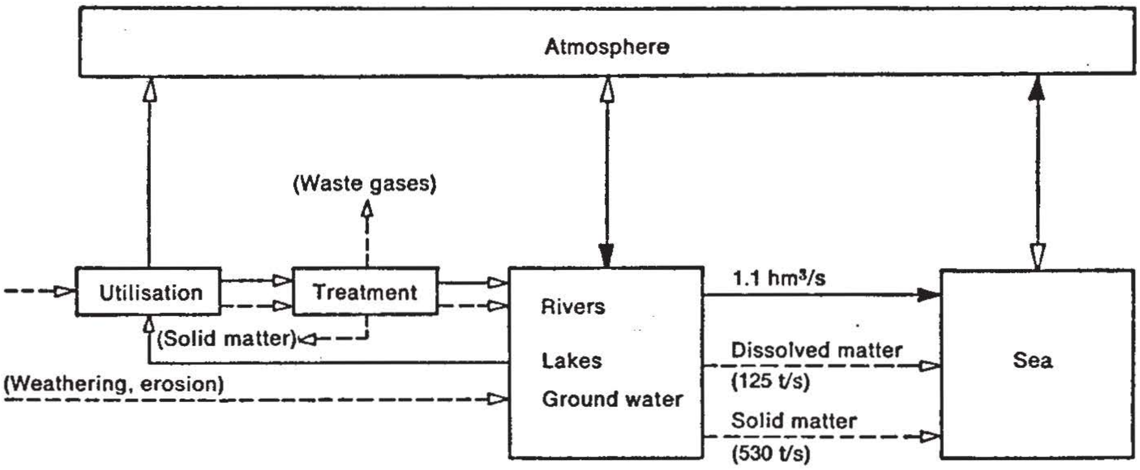


Figure 1 – *Transport of water-borne substances in the hydrological cycle*

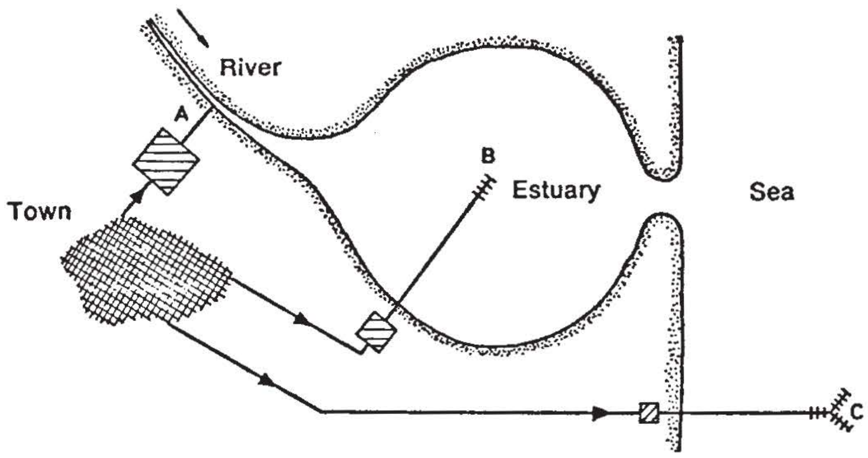
forms a natural reservoir and terminal point for all the substances contained in water; a fact which becomes particularly evident if we consider the residence times (water volume divided by flow rate) of various bodies of water – whereas the volume of water in a river is entirely renewed within days or weeks, replacement in the ocean must be measured on a geological time scale and, for our present purpose, may therefore be taken as infinite. Two immediate implications are that the overall pollution of the sea by non-decomposable substances becomes apparent only slowly and that, once that stage is reached, it is virtually impossible to remedy it.

In water utilization a proportion of the water is abstracted from the hydrological cycle for a very wide range of purposes, being finally restored to it after suitable treatment. Only a very small fraction of the water supply is actually consumed (and eventually evaporated); the utilization consists in essence of an enrichment with substances which, although subsequently partially removed in purification plants, are mainly returned to the hydrological system. Thus the problem is not so much whether nature provides sufficient reserves of water for human use (worldwide, water use accounts for about 2 % of the hydrological cycle) as the fact that increasing amounts of waterborne substances must be transported in the hydrological system while the quantity of water remains unchanged. The latter factor occasions a steadily growing pollution of inland waters and so, for coastal areas at least, it seems logical to investigate the possibility of discharging polluting matter directly into the ocean.

The planning task

Figure 2 compares the various possibilities of waste treatment and disposal available to a town near the coast. A combined purification plant and outfall structure is a system for removing waste which must, firstly, be adapted to the relevant water quality requirements and, secondly, be optimized according to economic aspects. If the available methods for discharging water in a river, estuary or ocean are compared, it will be seen that a much greater dilution can be achieved in the ocean than at other points of discharge.

This means that a correspondingly higher level of purification must be achieved in the disposal plant discharging into the river or the estuary in order to achieve the same concentration of pollutants in the environment (for example, a reduction in waste concentration by a factor of 150). Needless to say, a mechanical purification plant is also used to treat waste before it is discharged into the sea in order to remove certain substances such as oil which would otherwise rise to the surface and be transported at a com-



Outfall site	A	B	C
Initial attenuation at outfall site	10	30	150
Degree of purification required for same effect ($c = c_0/150$)	93 %	80 %	0
Degree of purification assumed for sewage plant	90 %	75 %	33 %
Pollutant concentration near discharge	$\frac{c_0}{100}$	$\frac{c_0}{120}$	$\frac{c_0}{225}$
Assumed least transport time to the shore	0	4h	12h
Maximum concentration of decomposable matter (with t_{90} = 4h) at the shore	$\frac{c_0}{100}$	$\frac{c_0}{1{,}200}$	$\frac{c_0}{225{,}000}$

t_{90} = the period in which the concentration is reduced to $0.1\ c_0$.

Figure 2 – *Different possibilities of water treatment and disposal after Pearson*

paratively rapid rate by wind action. Hence it may be conceded that a considerably reduced concentration of pollutants occurs with discharge into the sea when compared with discharge at inland sites. This is particularly true in the case of domestic sewage which has a relatively short decomposition time, so that for discharge at a sufficient distance from the coast (where the use is most intensive) much smaller concentrations are possible than in the case of inland outfalls.

For costing purposes the greater expenditure on a plant with fully biological purification stages (as used for inland disposal) must be compared with the cost of the (usually) longer transportation distances for marine outfalls. The latter have the inestimable advantage of extension potential in case the quantity of the sewage increases or if the water quality requirements are raised. In such cases the disposal plant for marine outfalls can be extended by incorporating additional purification stages: a possibility which has already been exhausted in the case of inland effluent disposal.

In designing a system for the harmless disposal of waste into the sea the civil engineer has to handle problems related to sanitary engineering, fluid mechanics design and construction techniques. In addition, he must co-operate with biologists and oceanographers. This is illustrated by considering the planning stages involved with a plant of this type.

The first step is to establish the water quality requirements, which entails determining the permissible coliform bacteria counts, turbidity levels, conditions concerning oil and grease layers, unpleasant smells, oxygen demand, etc. At the same time, areas subject to various regulations must be specified. The coastal zone is naturally the most important one because of its wide range of uses (where, for example, bathing water standards are required). Moreover, it is desirable to keep the upper water layers free from pollution since there the majority of human activities occur.

It is also essential to make a careful study of natural currents, temperature, salt content, the topography and character of the sea bed and of marine life. Attention must be paid to all of these and to land utilization factors when the site is selected.

The fluid-mechanics aspects of the design affect the proper functions of the structure and especially involve the question whether under the given conditions the site and arrangement of the outfalls can be developed in such a way as to fulfill the water quality requirements.

Finally, in addition to the above environmental aspects, economic and regional planning considerations are of crucial importance in the decision-making process.

The fluid-mechanics task

A typical marine outfall consists of a pipeline laid on the seabed, essentially at right angles to the coastline (Fig. 3). Since the seabed usually has only a slight gradient near the shore the pipeline has to be several kilometers in length if the discharge is to be sufficiently deep. To protect it against wave attack, the pipeline is laid underground as far as the surf zone and on the bottom in the deeper areas. The pipeline terminates in a diffusor with many small openings through which the waste water is discharged into the sea over a long stretch. The geometrical features of a waste outfall can be roughly summed up by saying that the horizontal dimensions of the body of water are very much greater than the length of the diffusor, which, in turn, is one order of magnitude greater than the depth of the water. The diameter of the diffusor and the distance between the nozzles are in the order of one meter and typical diameters of the nozzles are of the order of 10 cm.

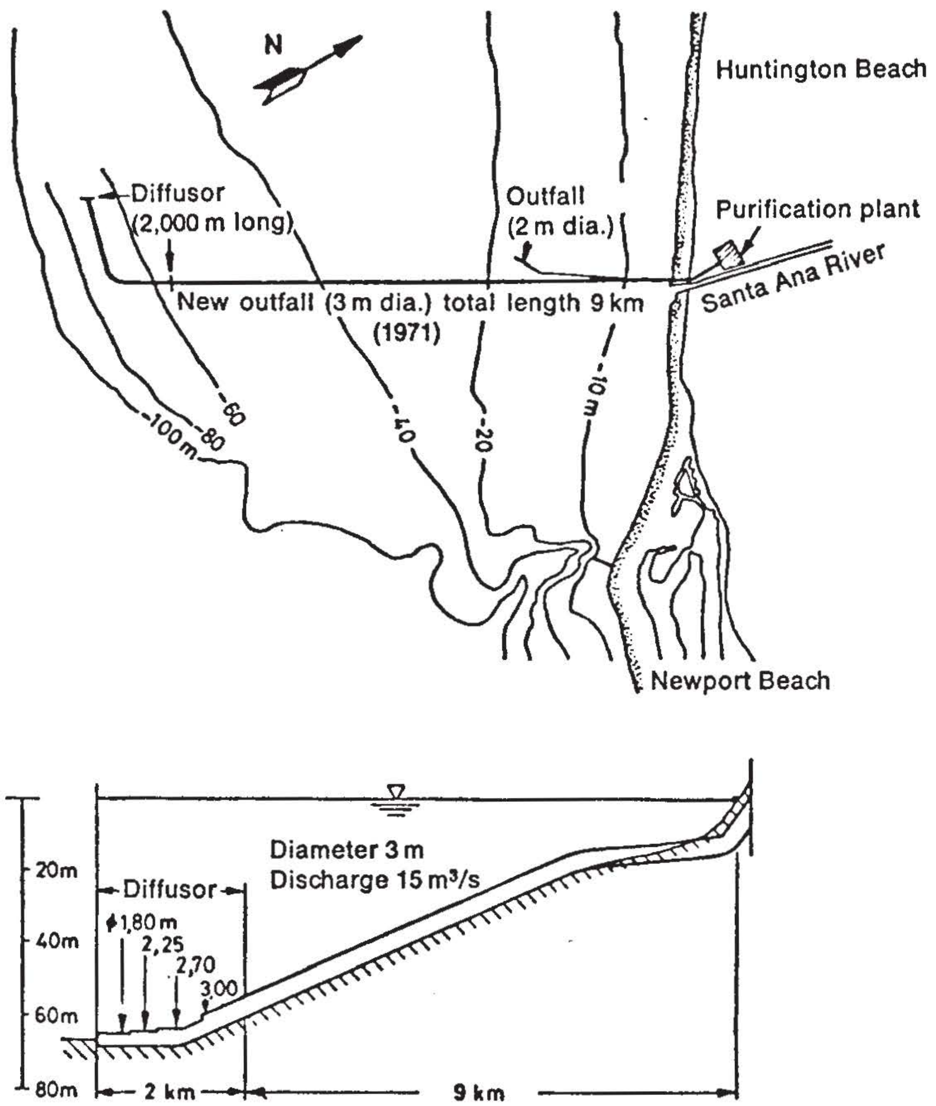
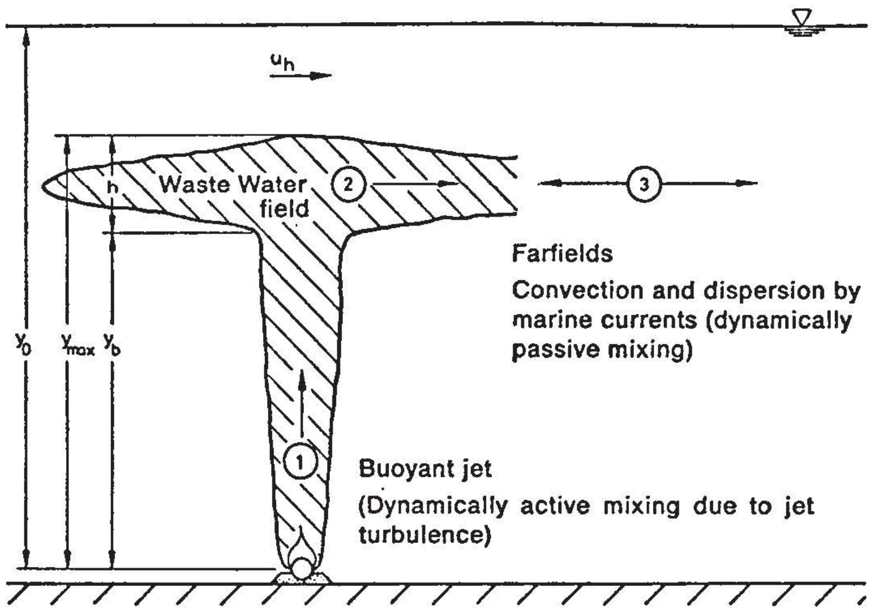


Figure 3 – *Example of a marine outfall* [11] *(Orange County, Submarine Outfall, California, U.S.A.)*

When designing a satisfactory functional outfall system, it is necessary to ensure not only that the outflow per unit length is kept as constant as possible throughout the entire diffusor, but also that sedimentation in the system and the inflow of salt water are prevented and that the loss of energy is kept as small as possible. However, these internal flow problems will not be considered here.

Instead, the essential problem is whether, under given conditions, an outfall can be planned in such a way that it fulfills the water quality requirements. Decisive factors for purification in waste outfalls are the mixing and dilution with sea water and also the chemico-biological decomposition and sterilization processes. In this respect the function of fluid-mechanics is to provide the laws governing the turbulent mixing and transport of the waste discharged into the sea. In this process, three successive phases can



Reference orders of magnitude			Realisable dilution:
Region	Length	Time	up to $10^{2.5}$ in the dynamically active region
1	Water depth	Minutes	up to $10^{0.5}$ in the dynamically passive region
2	Diffusor length	Hours	
3	Water body	Days	up to 10^3 through fluid-mechanics processes

Figure 4 – *Fluid-mechanics processes in marine outfalls*

be distinguished which are characterized by decreasing intensity of mixing and increasing dimensions in space and time (Fig. 4).

The discharged waste possesses both kinetic energy resulting from the discharge velocity and potential energy resulting from the difference in density of the waste water and the sea water. A momentum and buoyancy driven jet flow is produced in which the fluid moves with high velocity relative to the surrounding fluid (region 1). Owing to the velocity gradients, turbulent eddies produce transverse mixing, so that fluid from the surrounding area is being continually entrained into the flow. This mixing causes increasing "dilution" of the fluid originally discharged and thus a reduction in the concentration of pollutants with increasing distance from the outlet point.

During the phase of horizontal spread (region 2), the diluted waste spreads horizontally – either on the surface or, in a density-stratified water body, at the level of its neutral layer (at which the densities of the discharge and surroundings are equal). The horizontal spreading shows a tendency to reduce the vertical thickness of the sewage cloud.

After the original outfall energy is consumed, the diluted waste water is still concentrated within a "field" but behaves in the same way as the surrounding sea water and is "passively" carried by the prevailing currents in more or less the same way as the plume of smoke emitted from a chimney is carried along by the wind in the atmosphere. Some mixing still occurs in this third phase as a result of the natural turbulence of the ocean currents, although it is much weaker than in the phase of active mixing.

If we pause to consider that the dilution effect due to jet turbulence obtained very quickly in the immediate vicinity of the outlet is generally two orders of magnitude above the mixing effect caused by natural processes, it will immediately be evident that the fluid-mechanics of the near field is of crucial importance.

Mixing in buoyant jets

Buoyant jets can be classified according to the characteristics of the water into which they are introduced and according to the driving forces of the flow, the momentum (mass times velocity) and buoyancy (difference in mass from the recipient medium times gravitational acceleration) fluxes at the nozzle. A momentum jet is characterized by the fact that in absence of external forces the jet momentum remains constant with distance from the nozzle. In contrast to this, in an (always vertical) buoyant plume, the momentum flux increases along the distance steadily due to the buoyancy forces. A stable density stratification can change the flow field dramatically: the flow entrains denser water from the lower levels and gradually loses its upward momentum in consequence. Any further rise would encounter negative buoyancy and consequently the flow ceases at the neutral position and the fluid spreads horizontally. (This effect can also be observed when chimney smoke is discharged into the atmosphere during inversion weather.) Any cross-current in the water eventually causes a diversion of the buoyant jet in the direction of the cross-current.

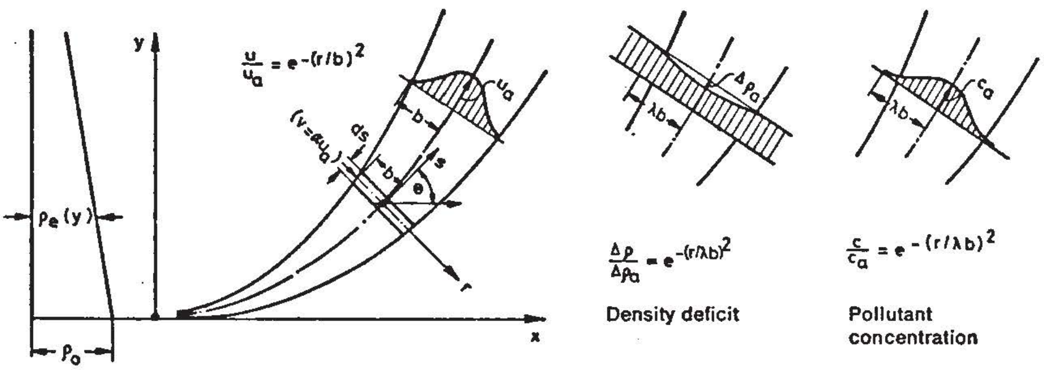
A dimensional analysis for flows entering a stationary body of fluid without density stratification is very instructive about the flow field [8]. Buoyant jets can be characterized by the densimetric Froude number.

$$Fr_d \equiv \frac{u_o}{\sqrt{\frac{\Delta\varphi o}{\varphi o}\ gdo}}$$

This number may be interpreted as the ratio of the momentum flux per unit time to the buoyancy of the jet. It follows from this that the classical free jet (momentum jet without buoyancy) is characterized by ($Fr_d = \infty$) and the pure plume is characterized by ($Fr_d = 0$). It has been verified in both these limiting cases [8] by dimensional analysis that the resultant velocity profile developments are similar and that the entrainment velocity v at the nominal jet boundary is proportional to the corresponding axial velocity u_a ($v = \alpha u_a$).

In analysing buoyant jets, it is now assumed that, in the light of the limiting cases, the velocity profiles are also similar and that ($v = u_a$) gives a first approximation for the entrainment. Similarity of the profiles is also presumed for the density deficit in the buoyant jet and for the concentration of dynamically neutral pollutants. In this connection it must, however, be borne in mind that scalar quantities are more quickly transported in the transverse direction by turbulence than is the vector momentum. The characteristic reference dimension for the extension in width of these quantities is accordingly expressed as λ times the width b, where λ is the ratio of turbulent mass to momentum exchange, which has a value greater than unity (Fig. 5).

For the analytical treatment of a fully turbulent buoyant jet discharging into an arbitrarily stratified water body of large lateral extension, we may adopt the usual boundary layer simplifications and the Boussinesq approxi-



Defining equations for round buoyant jets in a density-stratified fluid

1. Continuity	$\frac{d}{ds}\int_0^\infty 2\pi r u\,dr$	$= 2\pi b \alpha u_a$	$\therefore \frac{d}{ds}(u_a b^2)$	$= 2\alpha u_a b$
2. Vertical momentum flux	$\frac{d}{ds}\int_0^\infty 2\pi r \rho u (u \sin\theta)\,dr$	$= g\int_0^\infty 2\pi r(\rho_e - \rho)\,dr$	$\therefore \frac{d}{ds}\left(\frac{u_a^2 b^2}{2}\sin\theta_a\right)$	$= g\lambda^2 b^2\left(\frac{\rho_e - \rho_a}{\rho_o}\right)$
3. Horizontal momentum flux	$\frac{d}{ds}\int_0^\infty 2\pi r \rho u (u\cos\theta)\,dr = 0$		$\therefore \frac{d}{ds}\left(\frac{u_a^2 b^2}{2}\cos\theta_a\right)$	$= 0$
4. Density deficit (buoyancy flux)	$\frac{d}{ds}\int_0^\infty 2\pi r(\rho_o - \rho) g u\,dr$	$= 2\pi b \alpha u_a(\rho_a - \rho_e) g$	$\therefore \frac{d}{ds}\left[u_a b^2(\rho_e - \rho_a)\right]$	$= \frac{1+\lambda^2}{\lambda^2} b^2 u_a \frac{d\rho_e}{ds}$
5. Geometry	$\frac{dx_a}{ds}$	$= \cos\theta_a$		
6. Geometry	$\frac{dy_a}{ds}$	$= \sin\theta_a$		
7. Concentration of pollutants	$\frac{d}{ds}\int_0^\infty 2\pi r c u\,dr$	$= 0$	$\therefore \frac{d}{ds}(c_a u_a b^2) = 0 \rightarrow c u_a b^2 = \text{const} = c_o U_o b_o^2$	

Empirical coefficients: α, λ Unknowns: u_a ; b ; ρ_a ; x_a ; y_a ; θ_a ; c_a

Figure 5 – *Analytical formulae for round buoyant jets in a density-stratified fluid*

mation (small density variation), which leads to the defining equations given in Fig. 5 (in which the curvature of the flow axis is ignored). The continuity equation (1) (entrainment hypothesis) indicates that the increase in the volume flux along the jet is equal to the volume flux entrained laterally per unit length. The increase in vertical momentum flux is equal to the buoyancy force acting per unit length (2), whilst the horizontal momentum flux remains constant in the absence of external forces (3). The change in buoyancy flux (buoyancy per unit time) – related to the density φ_0 – is equal to the buoyancy of the entrained fluid per unit length (4). In a homogeneous recipient fluid, the buoyancy flux remains constant. When the jet is not vertically introduced, its axis follows a curved path: the locus of its axis is given by the geometrical relations (5) and (6). The volume flux of a conservative (not subject to decomposition processes) neutral tracer of the volume concentration c is constant along the jet (7).

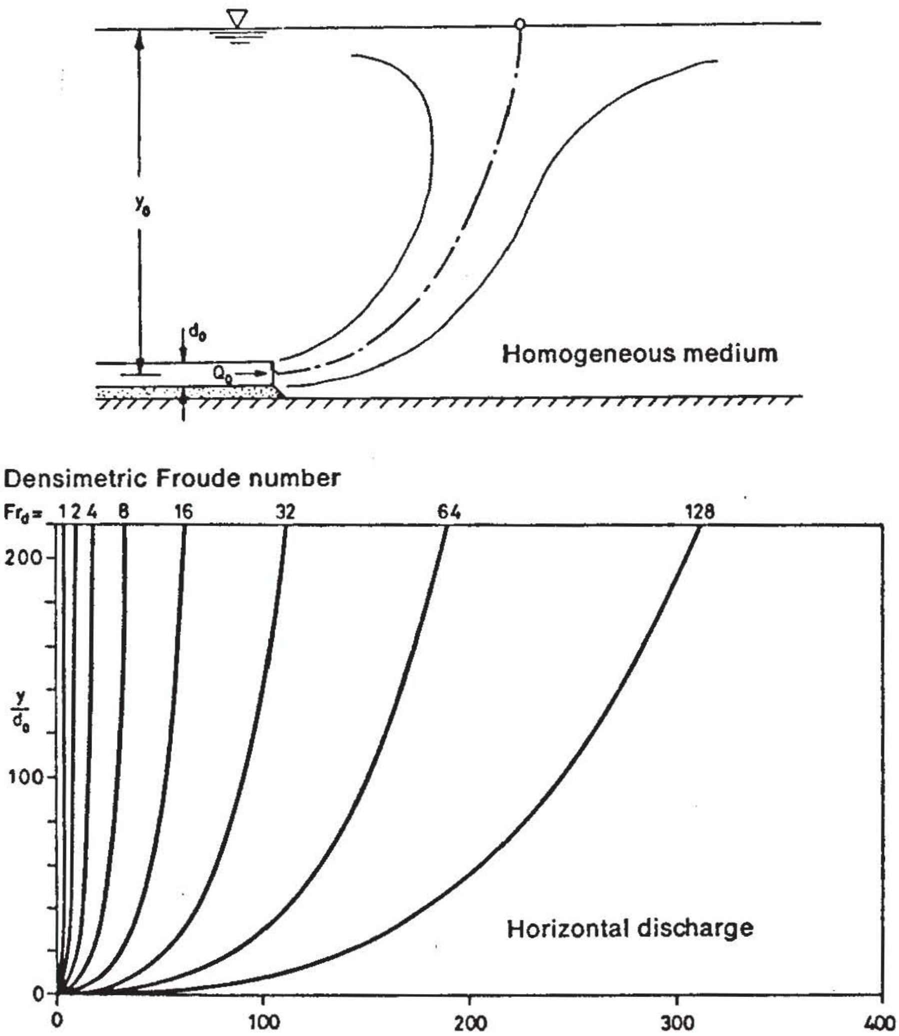


Figure 6 – *Discharge from an open pipe: trajectory of the jet axis*

When the above-mentioned similarity profiles for velocity and concentration are introduced, integration in a radial direction can be carried out and a system of ordinary differential equations with s as the sole independent variable is obtained. Consequently there are seven defining equations available for seven parameters: axial velocity, jet width, density deficit, position of the flow axis and pollutant concentration. These contain the already mentioned empirical constants α and λ. These equations can be solved numerically for prescribed initial values.

The system of equations proposed here can be employed for calculating the flow fields of round buoyant jets for arbitrary nozzle orientations and arbitrary (stable) density profiles of the recipient fluid. Figures 6 and 7 show example solutions for the case of a horizontal jet in a homogeneous fluid. The main feature of Fig. 6 is the locus of the flow axis for different Froude numbers. In the limiting case $Fr_d = 0$ (pure plume) the jet axis coincides with the y–axis. With increasing Froude number – i. e. with increasing significance of the horizontal momentum – the flow is laterally deflected, but finally there is always a vertical asymptote. Finally, for the pure momentum jet ($Fr_d = \infty$) the flow axis coincides with the x-axis. In Fig. 7 the dilution S of the waste water is plotted as a function of the height of the rise y/d_0 and the densimetric Froude number. The dilution S is defined here as

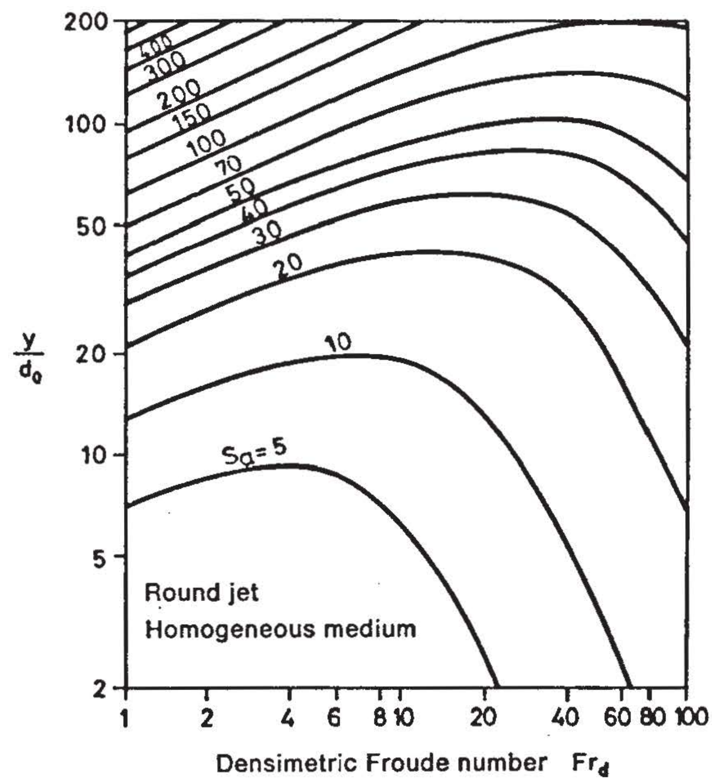


Figure 7 – *Dilution along the jet axis $S_a = c_o/c_a$ for horizontal discharges*

the inverse ratio of the pollutant concentration c to the original concentration c_0 at the nozzle. Thus along the flow axis the minimum dilution at any given point is $S_a = c_0/c_a$.

In view of the fact that as the Froude number – and therefore the discharge velocity – rises, so does the energy demand of the discharge, it is obvious that it is advantageous to keep the densimetric Froude number small when waste water is discharged. The majority of practical applications will accordingly be found in the upper left-hand corner of the diagram where small Froude numbers are combined with considerable depths. Here the solution approximates to the limiting case defined for the pure plume.

Finally, Fig. 8 illustrates how the results of the calculation can be directly applied to optimizing the design of outfalls. Assume that a flow volume Q_0 is discharged at a depth of water y_0 through an open horizontal pipe of diameter d_0 (Fig. 6) and that there is an attendant dilution at the surface of ($S_a = 10$) as represented by point A on the graph of the dilution expressed as a function of the relative depth of water and Froude number. It is required to find how this dilution can be increased by a factor of four (i. e. $S_a = 40$). For a given flow rate, there are three possibilities to achieve this:

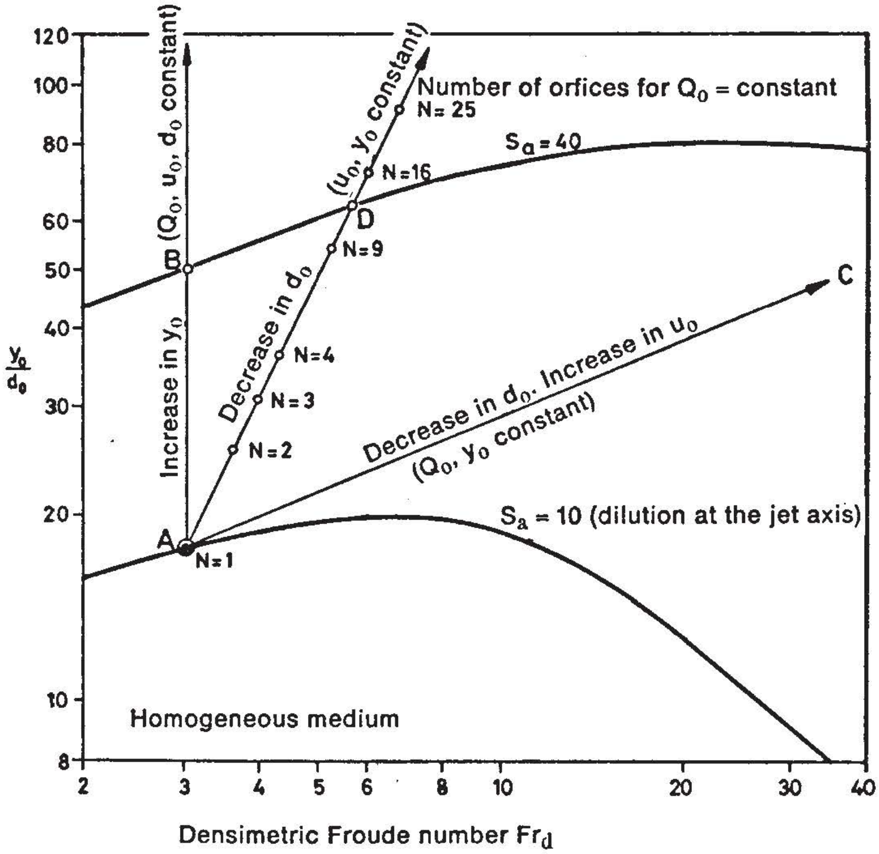


Figure 8 – *Possibilities for increasing mixing and dilution in horizontal outfalls after Brooks*

1. To increase the depth of the outfall y_0 (A → B), which would involve moving the outfall to an alternative (deeper) site;
2. To reduce the outlet cross-section d_0 and to increase the discharge velocity u_0 (A → C), which has the drawback of a greatly increased energy requirement;
3. To provide a number of small nozzles with constant total area (A → D). This method illustrates that the best way of increasing the dilution effect without changing the location and without an excessive rise in energy requirements is thus given by the adoption of a diffusor with a great number of small nozzles.

If it is decided to have a number of round jets in a series of nozzles, it is important to distinguish according to the distance between the nozzles and the water depth whether the jets will enter the sewage field individually or whether they form a plane jet (Fig. 9). If the diffusor has an alternating arrangement of the nozzles on each side, two plane jets may form which, because of the decreased entrainment flow from the region above the diffusor, are deflected towards each other and will finally merge into a single plane jet.

Plane jets can be analysed by methods exactly analogous to those used for round jets. Since waste water is usually discharged at great depths with small densimetric Froude numbers, the true situation is fairly accurately represented by the solution for the limiting case for the pure plume ($Fr_d = 0$).

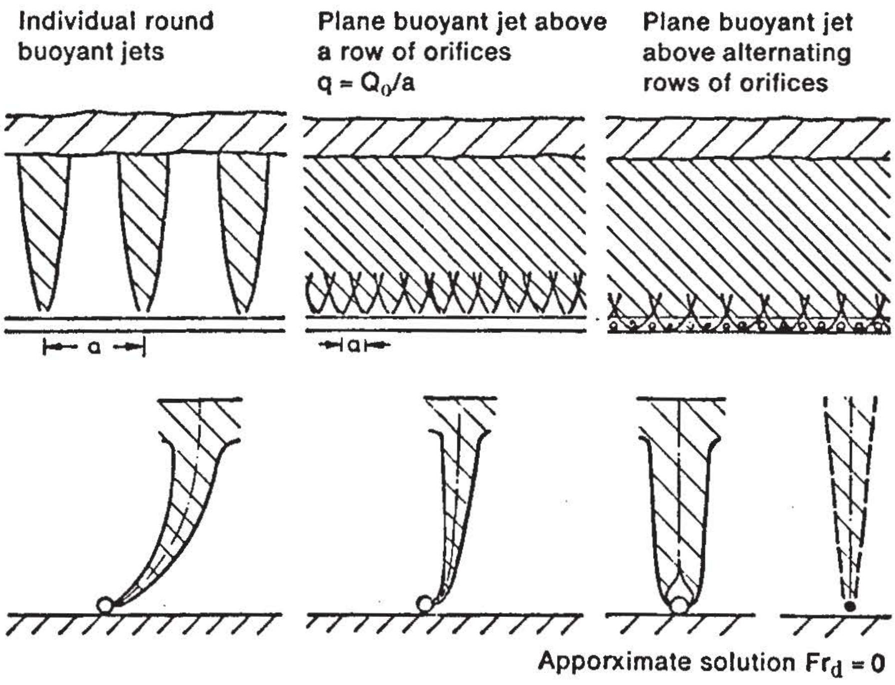


Figure 9 – *Series of orifices*

In a homogeneous fluid the defining equations have an especially simple form and can be solved in closed form. It is found that the axial velocity remains constant throughout the ascent and the width of the plume increases linearly:

$$\frac{u_a}{\left(\frac{\Delta\varphi o}{\varphi o}\, g\, \frac{Q_g}{l_o}\right)^{1/3}} = \left(\frac{1+\lambda^2}{2\alpha^2}\right)^{1/6} = 1.80$$

$$\frac{b}{y} = \frac{2\alpha}{\sqrt{\pi}} = 0.177$$

The dilution along the axis of flow is a function of the density difference of the total volume flux Q_g of the discharge of the diffusor length l_o and of the water depth y_o:

$$S_a = \underbrace{\left[\sqrt{2}\;\alpha\left(\frac{1+\lambda^2}{2\alpha^2}\right)^{1/6}\right]}_{=0.38}\left(\frac{\Delta\varphi o}{\varphi o}\, g\right)^{1/3} \frac{l_o^{2/3}\cdot y_o}{Q_g^{2/3}}$$

In a fluid with linear density stratification, the final height y_{max} of the plume is determined by the ratio of the kinematic buoyancy to the density gradient $(d\varphi_e/d\,y)$:

$$y_{max} = 2.84\,\frac{\left(\frac{\Delta\varphi_o}{\varphi_o}\, g\, \frac{Q_g}{l_o}\right)^{1/3}}{\left(\frac{-g}{\varphi_o}\,\frac{d\varphi_e}{dy}\right)^{1/2}}$$

The dilution reached on the flow axis at y_{max} may be expressed in a form analogous to the dilution in a homogeneous medium, in which case the depth of water y is replaced by the final height of ascent y_{max} and the constant of proportionality has a smaller numerical value:

$$S_a\,(y_{max}) = 0.31\left(\frac{\Delta\varphi o}{\varphi o}\, g\right)^{1/3} \frac{l_o^{2/3}\; y_{max}}{Q_g^{2/3}}$$

The mean dilution in any cross-section of the plume is directly proportional to the value on the plume axis. These relationships are very useful in the preliminary design of outfalls. For example, for a given density difference and given discharge, it will be seen that the same degree of dilution can be obtained with a smaller depth of water (or final height of ascent) and greater diffusor length as, alternatively, with greater depth of water and a correspondingly shorter diffusor. The approximate solutions are always on the safe side, i. e. in comparison with the buoyant jet, the final height of ascent is over-estimated and the dilution is under-estimated.

Dispersion and transport of the waste water field

When detailed application is made of the findings regarding buoyant jets in order to investigate the initial dilution of outfalls, it must be borne in mind that the jets will enter the waste water field, which is extended horizontally and which can exhibit a considerable layer thickness h, depending upon the prevailing flow conditions of the sea. It is obvious that there is no further dilution within the body of waste water. The initial dilution due to the buoyant jet is therefore given the value it has attained at the time of entry into the body of waste water at the height y_b (Fig. 4). A rough estimate of the thickness h of the waste water field above he diffusor can be made from the continuity requirement that the volume of flow carried to the waste water field by the buoyant jets must be conveyed "passively" (i. e. with the velocity u_h) by the marine current. It will accordingly be seen that the removal of the main body of waste water by marine currents is of decisive importance for satisfactory waste water disposal. In situations where this removal is very slow, there will be a considerable build-up of depth of waste water and, in the extreme case ($u_h = 0$), it will extend throughout the entire depth of water. It is obvious that the diluting action of the buoyant jets is no longer effective in such circumstances; on the contrary, the initial dilution is absolutely governed by the bulk movement of the waste water by marine currents and thus by the water depth and current velocity u_h. Such conditions are frequently encountered in cooling water discharges with large discharges into shallow water.

Therefore, when optimizing an outfall, an essential part is played by the depth at which the waste water is becoming "neutral". On the one hand, the waste water field must be kept at a sufficient depth below the surface, but on the other hand, the deeper the waste water lies, the less is the initial dilution. Decisive for the level at which the waste water field is located is the density stratification of the sea at the outfall site. This is subject to seasonal variations and so allowance must be made for seasonal differences in the elevation of the waste water field.

The diluted field of waste water is liable to convection and dispersion by ocean currents. In this phase, the process is usually studied by means of horizontal, two-dimensional numerical models. The basis of such models are the vertically integrated equations of motion in two horizontal directions and the continuity equation specifying the depth of water and the velocity components u_h and v_h. The solution relies on field methods in which the flow parameters are calculated in discrete steps by iteration at all nodal points of a specified grid for the entire flow field.

For calculating transport and dispersion effects there are, in addition to the three equations already mentioned, two others; the equation of state for the density, which in the general case is a function of the concentration c of the material contained in the water, and the transport equation for that material. However, if the treatment is restricted to dynamically passive materials, then the density φ can be considered as constant and the transport equation can be isolated from the flow field equations. The velocities and the water levels are given by the solutions of the first three equations and the results are then incorporated in the transport equation to find the concentration c.

Needless to say, it is impossible to determine the nearfield of outfalls by means of horizontal two-dimensional models, but the procedure proves successful for the farfield, as there the essential conditions are fulfilled. Therefore, it makes sense to calculate the farfield by means of two-dimensional hydrodynamic-numerical models.

A major difficulty in calculating the farfield transport lies in obtaining realistic diffusion coefficients for the transport equation. It has been found that in diffusion due to marine turbulence a distinction must at least be drawn between a horizontal and a vertical diffusion coefficient. The vertical mixing appears to decrease as stability increases and thus as the Richardson number increases. The horizontal diffusion coefficient ε_h varies over many orders of magnitude and is correlated with the overall dimensions of the diffusing field. In spite of considerable scatter the "4/3 Rule" proposed by Richardson in 1926 seems to hold good: in this the horizontal diffusion coefficient is taken to be proportional to the horizontal dimension $l^{4/3}$ of the diffusing field (Fig. 10). The proportionality factor shows large scatter due to the influence of density stratification, vertical velocity gradients or the depth of water, which all have been neglected in this law. In general, correlations according to the 4/3 rule are encouraging, although not conclusive.

In view of these uncertainties in the assumed physical parameters, it seems expedient and adequate at present to assess convection and dispersion by marine currents by means of simplified approximate solutions. A method developed by Brooks [1] is useful here, whereby the spreading and dilution of a waste water outfall is calculated in a laterally unrestricted steady ocean current considering horizontal two-dimensional motion (ignoring vertical diffusion). This method takes account of the way in which the diffusion coefficients grow with the dimensions of the waste water field as in Fig. 10.

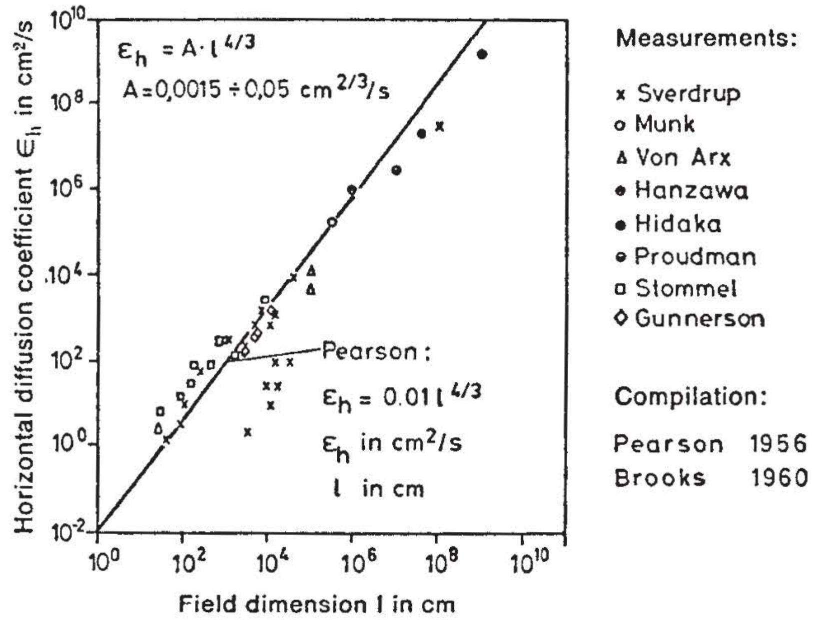


Figure 10 – *Field data for the horizontal diffusion coefficients* ε_h

For non-decomposable pollutants, the solution is that given in Fig. 11. Estimations by this method always lie on the safe side in so far as the true data always differ from those assumed here by tending to greater dilution.

Finally, mention must be made once more of the fact that hydrodynamic dilution in itself is not a purifying process. Purification depends, first and foremost, upon the chemico-biological decomposition and sterilization processes to which the waste water is exposed. All that is achieved by hydrodynamic dilution is a very rapid reduction in the local concentration of pollutants, the maximum attainable reduction factor being about 10^3. Yet some requirements are even more stringent. For example, if mechanically treated sewage with a coliform bacteria count of about 10^6/ml is discharged, then achieving bathing water standards for coliform bacteria counts of 10/ml corresponds to a required reduction factor of 10^5. This can be managed only by ensuring that, in addition to the hydrodynamic dilution, the minimum retention period of the waste water before it reaches the coastline (or another conservation area) is long enough for decomposition and sterilization processes to become effective. The time-scale adopted for this purpose is the period within which the concentration is reduced to 10 % of its original value. This is a function of the local marine biology and lies in the Pacific, for instance, between 2 and 8h.

Final remarks

With careful planning, sewage outfalls into the sea offer, despite their enormous scale, an economical and risk-free means of disposing of wastes

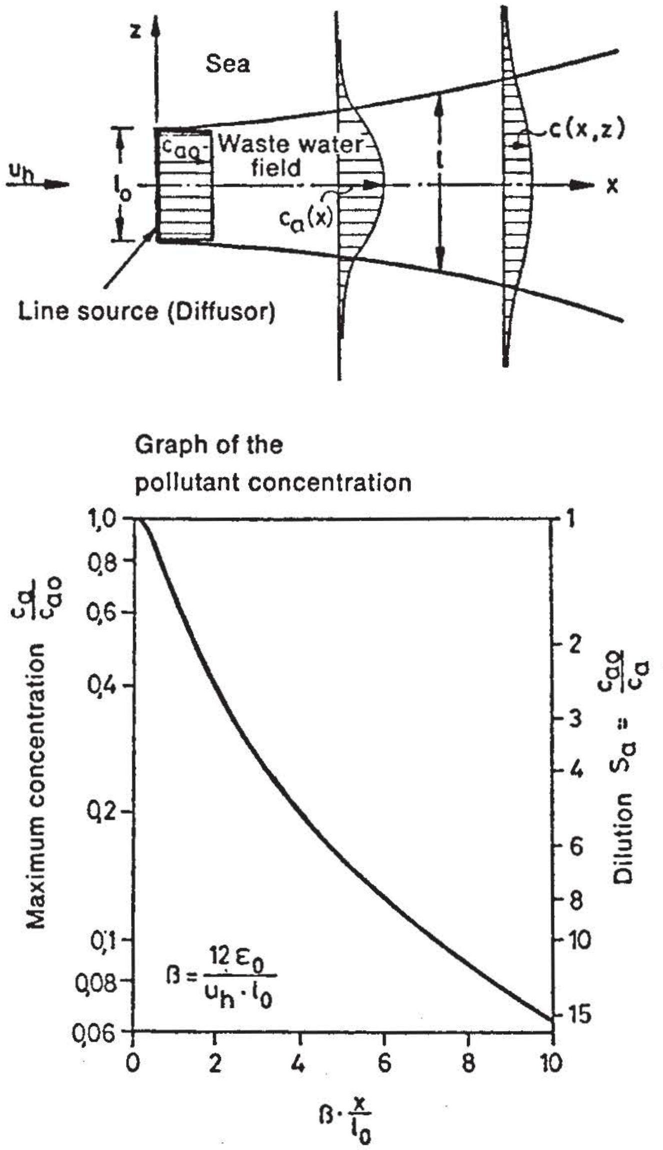


Figure 11 – *Transport and mixing in the farfield after Brooks* [1]

with decomposition times in the order of days. However, non-degradable and toxic substances must be kept well away from the sea at all costs.

Hydrodynamic dilution makes a crucial contribution to the purification effect at outfalls, although it is not sufficient by itself. The waste water can be very quickly diluted up to several hundredfold in the immediate vicinity of the outfall.

There is still no comprehensive fluid-mechanics model for prognosticating the mixing and transport of discharged waste water and a good deal of further research is required. Meanwhile, we must be content with partial models (integral methods for the nearfield, two-dimensional numerical models for the farfield) which adequately cover only a limited area and we have to combine these with the aid of engineering concepts to a rational design.

The siting and construction of the outfalls is of crucial significance both for the degree of active mixing and dilution in the nearfield and for the possibility of keeping the waste water field below the surface, if the sea is density stratified. It is for this crucial buoyant jet region that the fluid mechanics methods of calculation are most advanced.

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