CONTROLLING OCEAN POLLUTION

by Norman H. Brooks

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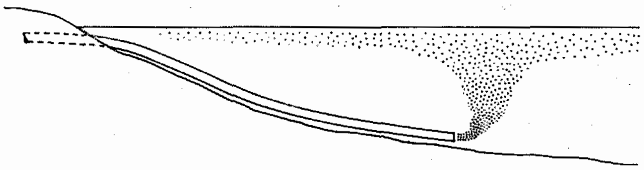
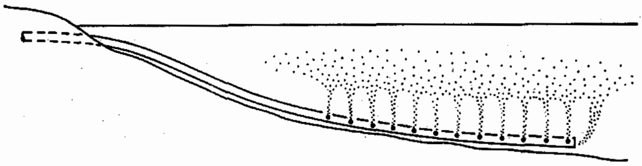
Sewage disposal into the ocean has come a long way from the time when there was indiscriminate dumping of wastes. The alarming ocean pollution that resulted from such practice has, in most places, been virtually eliminated in recent years. Today disposal is a carefully controlled operation based on extensive engineering research and design.

However, up until 10 years ago it was the usual practice to discharge sewage effluent from the end of a pipe or submarine outfall in a single large stream. The buoyancy of such a flow was so strong in relation to its mixing rate that the effluent plume would invariably rise to the surface and spread as a surface current. Pollution of the shoreline was likely when onshore currents occurred.



However, in the last decade there have been two significant advances in techniques of sewage disposal into the ocean. First, the natural density stratification of the ocean has been used to great benefit in keeping waste discharges submerged in the lower layers of the ocean. Second, very large multiple-jet diffusers have been successfully designed and operated without clogging or maldistribution of flow. Diffusers greatly increase the dilution of sewage effluent with seawater, and dilutions of 200 parts of seawater to one part of sewage effluent are now commonly achieved. It is only by this new technique of using a large number of small, widely-spaced jets that full advantage can be taken of the slight but definite density stratification patterns in the ocean.



A very large outfall and diffuser was put into operation by the County Sanitation Districts of Los Angeles in December 1965 at Whites Point on the Palos Verdes Peninsula, a few miles west of San Pedro. It is a submerged concrete pipeline 11,880 feet long, with 742 circular holes, or diffuser ports, arranged in pairs, spaced every 12 feet in the last 4,440 feet (the diffuser section). This is probably the largest number of ports ever used in an outfall diffuser. The depth at the diffuser ports ranges from 165 feet to 190 feet at the far end. The diameter of the ports varies from 2.55 to 3.60 inches, except for a few experimental ports of 2.00 inches at the shallower end. A complicated hydraulic analysis had to be made to determine the various port diameters required to ensure satisfactory hydraulic performance over the full range of flow. The pipeline diameter also changes size in the diffuser section, starting at 120 inches, then reducing to 102, and finally to 72 inches at the far end.

Although there are three other, older outfalls at Whites Point (60, 72, and 90 inches in diameter), the new pipe is large enough to carry the entire present-day sewage flow of 308 million gallons per day for the outfall system of the County Sanitation Districts. The older outfalls will be used as required to handle the increasing flows in the future. The system serves a population of 3,700,000 people living in an area of 608 square miles in the southern and eastern parts of the Los Angeles metropolitan area. The other major system in the Los Angeles area is operated by the City of Los Angeles; it discharges 304 million gallons per day through a five-mile-long outfall in Santa Monica Bay and serves 3,000,000 people. It is 12 feet in diameter and has two diffuser pipes, each 3,984 feet long, with 84 ports, at an average depth of 185 feet.

Sewage disposal systems

Generally, sewage disposal systems involve *collection, treatment,* and *dispersion.* All water used in man's activities ultimately must be returned to the water environment, unless evaporated. In large metropolitan areas domestic sewage and industrial wastes are collected by a system of sewers to central locations where the treatment and ultimate disposal can be closely controlled by engineers. It is interesting to note that one of the difficult problems of air pollution is that it is impractical to collect "used" air on a community-wide basis for treatment and disposal; instead we must impose directly on the consumer (such as the owner of an automobile) some responsibility for control of air pollution.

Strict rules prohibit industries from dumping into the sewers any highly obnoxious wastes which would have an adverse effect on either the ocean or the treatment plant operation. Furthermore, storm water must be excluded because it would grossly overtax the sanitary sewer system. For example, the daily mean flow of 308 million gallons collected by the County Sanitation Districts is equivalent to only 0.03 inch in water depth per day distributed over the drainage area. When it rains several inches in one day, the storm runoff may be tens of times larger than the flow which can be taken in the sanitary sewers. It is unforunate that many Eastern cities have sewers that allow the sanitary sewage to become mixed with the storm runoff, and to overflow into the natural watercourses whenever sewage treatment plants cannot handle the huge flows.

Ocean disposal

To plan a new system for ocean sewage disposal the engineer must start by considering the water quality standards to be met in the ocean environment—including maximum allowable bacteria concentrations, maximum increase in turbidity, limitations on any grease, absence of odors, minimum dissolved oxygen, absence of floating or suspended solids of recognizable sewage origin, or any other aesthetically unacceptable condition. The State of California, for example, has many detailed and strict requirements related to all of the foregoing characteristics; nonetheless, huge quantities of sewage effluent may be dispersed from properly controlled outfall systems without pollution.

Usually only *primary* treatment of sewage and industrial wastes is required, as in the case of the two large Los Angeles systems and the new San Diego sewerage system. Such treatment includes screening; sedimentation for removal of settleable solids, floatable solids, and grease; and chlorination if required for control of bacteria and viruses. The City of Los Angeles and the City of San Diego do not have to chlorinate at all to meet the rigid bacterial requirements of the state, while the County Sanitation Districts chlorinates its effluent only for a few days in the winter when the stratification in the ocean disappears. In all cases the dilution of the effluents with seawater is so great that all the other standards are very easily met after just the primary treatment.

The solids or sludge collected in the treatment plant are subjected to anaerobic decomposition in large digestion tanks, where sludge is reduced to a relatively stable humus-like liquid material of very fine particles in suspension. There is insufficient demand for all the digested sludge as fertilizer, so it is often pumped to the ocean also, either through a separate small outfall (as for the City of Los Angeles) or mixed with the sewage effluent (as by the County Sanitation Districts). In neither instance has the buildup of deposits on the bottom been progressive, because organisms and currents cause a gradual disappearance or assimilation into the natural bottom sediments.

If the outfalls in the Los Angeles area were not equipped with large diffusers, very expensive secondary treatment would be necessary to provide the necessary biodegradation of the sewage effluent to prevent pollution. In effect, the ocean provides the secondary treatment. The ocean already does this with organic wastes from natural ocean life. Thus, the main problem is to provide wide enough dispersal of man's effluents so as not to overtax the ocean and create aesthetic nuisances.

The design of ocean outfalls requires detailed oceanographic surveys to determine salinity, temperature, and density stratification; current speeds, directions, and frequencies; and submarine topography and geology. For future evaluation of the effects of the discharge, the characteristics of the marine biology and the turbidity and dissolved oxygen levels should also be measured before waste discharge is started.

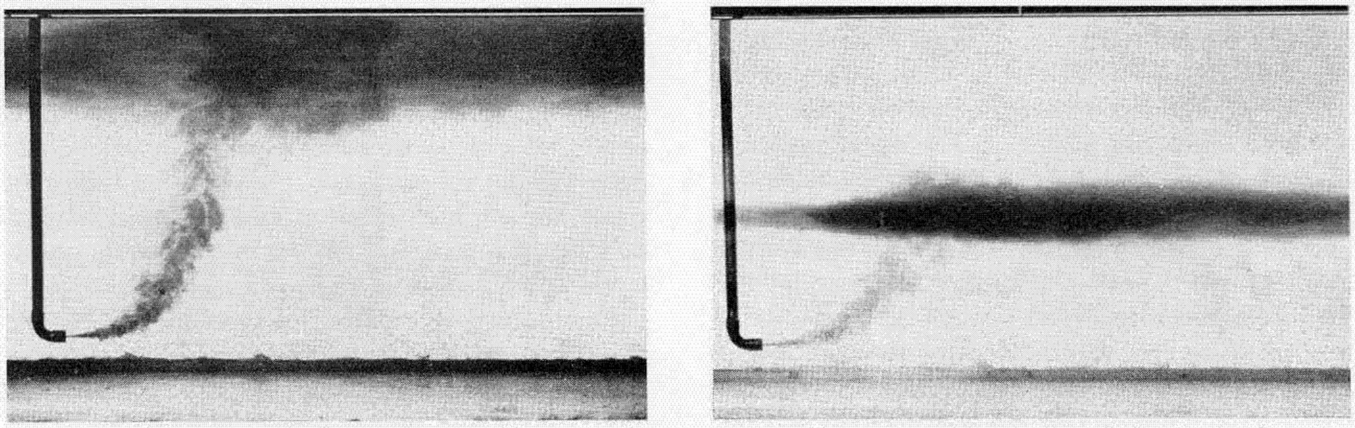
The turbulent diffusion of the sewage effluent occurs in two stages. First there is the jet or plume mixing near the diffuser pipes, which is controlled by the nature of the manmade diffuser. Second is the movement of the diluted sewage "cloud" by the ocean currents and further dilution by the natural ocean turbulence. For the greatest security it is good practice to achieve as much manmade mixing as feasible right at the diffuser and to avoid depending too heavily on the natural dispersive mechanisms of the ocean, which are more difficult to predict analytically and statistically. Diffuser pipes are oriented, within allowable limits of the bottom topography, in directions to intercept as much of the ocean current as possible for critical shoreward current directions. The number and spacing of ports is based on considerations of the behavior of the buoyant jets discharged from the ports. The port diameters are selected to make the "inside" hydraulics of the diffuser correct for a good manifold.

Buoyant plumes

The behavior of buoyant jets and plumes is one of several density-stratified flow problems which have been studied in recent years in Caltech's W.M. Keck Laboratory of Hydraulics and Water Resources under sponsorship of the U.S. Public Health Service. Density-stratified flows are those in which small variations in the weight of the fluid have a marked effect on the over-all flow pattern. For example, if fresh water is jetted into a homogeneous tankful of salt water, the slight buoyancy of the fresh-water stream will cause a horizontal jet to deflect upward. The fresh water begins as a submerged jet which is a flow dominated by the initial momentum. It then changes to a buoyant plume, a rising current strongly dominated by buoyancy and not influenced much by its initial momentum. The fresh water is, of course, mixed with the salt water as the surrounding fluid is mixed into the jet by the strong turbulence, and the density difference between the discharge and the ambient fluid decreases. But the plume will always remain slightly lighter than its surroundings because of its original fresh-water component, and it will rise until it reaches the water surface and spreads out laterally.

Effect of density stratification

A remarkable change in the flow pattern occurs when there is a slight gradation of density in the ambient fluid, caused by temperature and salinity changes with depth. In the ocean the stratification is almost always hydrodynamically stable, with warmer (or less saline) layers at the top. In the laboratory, the ambient salt water is stratified by



These two laboratory tank experiments illustrate the effect of density stratification in the water. Above, the water is of uniform density, and the buoyant plume rises to the surface. However, a slight density layering in the water stops the rising plume and keeps the cloud completely submerged.

filling the tank very slowly with thin layers of progressively decreasing salt content at the same temperature; the "staircase" variation of density is soon smoothed into a uniform gradient by molecular diffusion.

In the stratified environment the buoyant plume may no longer rise to the surface because the plume loses its buoyancy before it gets there. In the experiment illustrated on the previous page, the specific gravity in the tank at the bottom was 1.026, decreasing uniformly to 1.022 at the surface; the fresh-water jet was at 1.001. Denser water entrained into the plume near the bottom produced a mixture slightly heavier than the ambient fluid at a higher level. If each part of the fresh-water discharge of specific gravity 1.001 is mixed with 30 parts of bottom salt water at 1.026, the resulting mixture has a density of 1.0251, which is considerably heavier than the salt water at the surface (1.022).

Actually, the density of the entrained fluid decreases as the plume rises; nonetheless, a point of neutral buoyancy will be reached at which the fresh-water component is just counter-balanced with denser water entrained from the lower levels of the tank.

Theoretical investigations

The behavior of buoyant plumes in a stratified environment has been investigated theoretically by Robert C. Y. Koh, a recent Caltech research fellow, Loh-nien Fan, a present PhD candidate, and the writer. Numerical solutions for the trajectories and dilutions were obtained, using the Caltech IBM 7094 computer, for various initial conditions and density gradients of the environment. The theoretical solutions have been found to agree well with laboratory experiments and observed sewage plumes in the ocean.

One of the most interesting applications of the theory is the prediction of the maximum height of rise of a plume in a stratified environment. This is of special interest in the ocean, where submergence of the cloud of mixed sewage and seawater is beneficial in controlling pollution. The equations show that the maximum height of rise may be made less than the total depth by making the discharge (per port) sufficiently small in relation to the density gradient and the other quantities in the equations. To produce a submerged sewage cloud one must first measure the natural density stratification in the ocean and then design a diffuser to produce small enough jets so that the stratification may act as the brake on the buoyant rise.

Off the southern California coast there is strong thermal stratification in the summer. For example, the surface water may typically be at 65° to 70°F while the water at 200 feet is only 50°. At about 50 feet there is a relatively steep temperature gradient in a zone called the thermocline; above and below the thermocline there is a gradual decrease in temperature with depth. In the fall and early winter the thermocline sinks lower, and the stratification becomes weaker. In the spring the thermocline condition is established again by the increased solar heating of the upper layers. With rare exception the stratification is always stable (i.e., the density increases with depth below the surface).

The density stratification for coastal waters varies with the time of year. For example, in January off Point Loma near San Diego there is a difference in specific gravity from bottom (200 feet) to top of only 0.00022, which corresponds to a temperature differential of 2°F; in July it is 0.00220, for a temperature difference of 18° F.

Predicting submergence

The rate of change of density with depth is never exactly constant, but for a first approximation it may be assumed to be so. The new San Diego ocean outfall at Point Loma (put in service in 1963) discharges at a depth of about 200 feet through 58 horizontal ports more than two miles from shore.

For 1965 the mean flow per port was 1.5 cubic feet per second. According to our theory, to achieve submergence of the diluted cloud the density differential for the 200-foot depth must be greater than 0.00018, which is the case throughout the year now. The operation of the outfall has indeed confirmed this theoretical prediction; the sewage effluent cloud has never been observed at the surface. Ultimately the peak flow will increase to more than 6 cubic feet per second per port, and the required differential for submergence will increase to 0.00048. Submergence will still occur for approximately 11 months each year, with surfacing predicted only in January. Even then the treated sewage effluent will be diluted with approximately 170 times as much ocean water by the time it reaches the surface. Thus, even without submergence, the pollution is largely controlled by high dilution and by rapid natural die-off of bacteria and viruses in the hostile ocean environment.

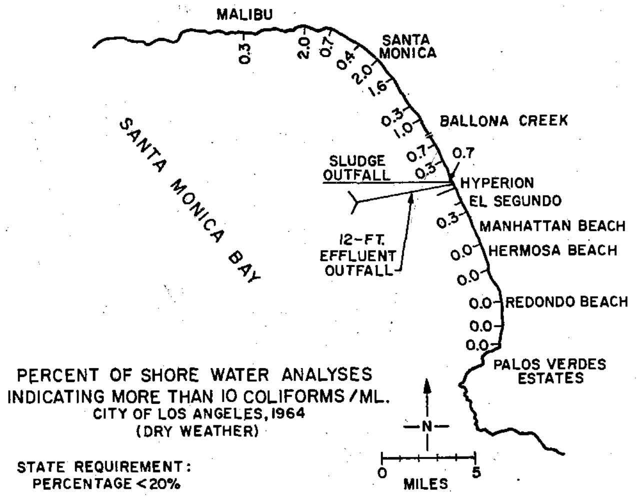
For the five-mile outfall of the City of Los Angeles, at present flows the theory predicts that the sewage field will be submerged when the temperature differential between the 185-foot depth and the surface is 3.7°F. In fact, several years of observation have indicated that complete submergence occurs when the temperature differential is more than 2°F. With all the possible sources of discrepancy—such as non-linearity of the density gradient and effect of the currents—the basic consistency of the results is again good and demonstrates that the theory is reasonably reliable for design purposes.

Results in Santa Monica Bay

The successful operation of an ocean sewage disposal system certainly involves more than the behavior of the jets and plumes near the outfall diffuser pipes. After the sewage effluent cloud is formed, whether submerged or not, it is carried away by the ocean current, and further turbulent diffusion takes place. The organisms in the cloud rapidly die off in the hostile ocean environment. For example, the coliform bacteria may be expected to die off at the rate of 90 percent every 4 to 5 hours, or faster. The final result may best be judged by the quality of the water along the shorelines, the most important area to protect for the health and enjoyment of the public.

For an example, consider the 20 miles of beaches along Santa Monica Bay. Even as recently as the 1940s about 10 miles of beach were heavily polluted with sewage discharge by the City of Los Angeles. Since then there has been a vast improvement because of the extensive new sewage treatment plant at Hyperion and the five-mile-long ocean outfall with a very large diffuser.

In 1964 no sampling station along the Los Angeles beaches had more than 2 percent of its samples exceeding a coliform bacteria count of 10 per milliliter (considered to be the threshold indicator for a detectable effect of water of sewage origin). The State of California requires that no more than 20 percent of the samples exceed that count. In other words, even at the worst station the occurrence of counts of 10 or more was less than one-tenth as frequent as is allowed by the state. For the over-all monitoring program on the shore only 31 samples out of 5,219 exceeded the standard in dry weather. (Samples during periods of storm are excluded because some low-level pollution is caused by the outflow from storm drains, which obscures the effect of the sewage outfall.)



Los Angeles beaches, badly polluted 20 years ago, are extremely clean today as a result of the use of diffusers that keep the effluent well submerged.

The sewage effluent itself has a coliform bacteria concentration of between 500,000 and 1,000,000 per milliliter as it leaves the diffuser pipe. Therefore, the combined action of dilution and die-off must bring about an over-all reduction by a factor of 100,000 in the ocean. Typically, the dilution might account for a factor of 500, with the remaining factor of 200 or more being due to die-off.

Future of ocean disposal

Ocean outfalls will not become obsolete even when much of the wastewater is eventually reclaimed for re-use. With growing demands for water there will undoubtedly be extensive wastewater reclamation in the Los Angeles area, because such water is much cheaper than de-salted seawater. Wastewater is already being reclaimed on a small scale, but there will always be substantial outflows to the ocean because only part of the sewage flows can be reclaimed and reused. Some types of industrial wastes are unsuitable for reclamation but may be discharged to the ocean. Furthermore, the waste products from the wastewater reclamation plants must go somewhere, and the ocean is the most feasible place.

New diffusion structures have virtually eliminated many pollution problems. There is no danger of ocean transmission of communicable diseases in areas such as Los Angeles and San Diego, nor are there any aesthetically objectionable conditions whatever in the ocean. In fact, the layman would have the greatest difficulty finding any evidence at all of waste disposal. However, there are some subtle ecological changes taking place in the ocean environment due to the waste discharges. These changes are being identified and evaluated through biological research, such as the kelp and sea urchin studies by Wheeler North, associate professor of environmental health engineering at Caltech. Man has never succeeded in completely avoiding ecological changes, but by using fluid mechanics to obtain high dispersion we are trying to minimize these long-range effects.