HYDRAULICS AND SUSTAINABLE WASTEWATER DISPOSAL IN RURAL COASTAL COMMUNITIES

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Contents

Summary

When planning for the treatment and disposal of municipal wastes, coastal communities have a number of options. Like inland towns they can utilize full waste treatment in a conventional secondary treatment plant and use traditional methods to dispose of sludge and other detritus. An alternative, however, is to use a well designed marine outfall to ensure thorough mixing with ocean waters, and to permit natural stabilization of the wastes in the ocean. If done correctly, the receiving waters will assimilate the wastes, and the process can, indeed, be beneficial in some nutrient deficient waters. It is, however, necessary to ensure correct design of the outfall and to ensure that the receiving waters and effluent are such that the wastes can be assimilated without environmental or aesthetic harm. This article compares the environmental effects of secondary treatment with those of a marine outfall, and shows that the marine outfall is a viable alternative in many cases. A case study is provided, and hydraulic design details are given, together with a discussion of environmental and financial considerations (see *Storm Water Drainage and Effluent Disposal; Hydraulic Structures in Urban Drainage Systems; Wastewater Treatment; Effluent Disposal*).

1. Introduction

Small communities around the world have many problems in treating and disposing of their domestic effluents. Typically, the towns have a low tax base and need a reliable system with low maintenance, operating and repair costs together, with minimal operator attention. The normal solution, a package treatment plant of some kind, will often prove to be too expensive to run, too difficult for an untrained operator to operate, and too costly to repair when it breaks down. Reduced performance and breakdowns over the years then lead to environmental degradation. In the long run such systems are often unsustainable (see *Guidelines for Sustainable Community Water Supply and Sanitation Projects*).

An alternative for coastal communities would be to use a well designed marine outfall. The outfall provides a sustainable system whereby domestic effluents (or biodegradable industrial effluents) may be discharged to the sea while ensuring the maintenance of acceptable environmental conditions in the receiving waters. Essentially, the process involves some pretreatment to remove large suspended solids and floating material, followed by discharge offshore at a depth well below low water. Provided wind, wave, and current conditions are suitable, outfalls have been shown to provide favorable reductions in BOD at less cost and at less damage to the environment than do conventional land based treatment plants (see *Hydraulic Structures in Coastal Defense; Model Studies of Ocean Waves; The Uses and Protection of Materials in the Ocean Environment*).

A properly designed outfall will generally involve some preliminary treatment—at the very least screens and comminutors or grinder pumps to break up fecal matter. This would be followed by discharge at depth through a submerged pipe discharging well offshore, through one, or more, outfall ports; the distance, depth and number of ports being dependent on the effluent flow, the condition of the receiving water and the desired dilution. A typical arrangement is shown in Figure 1.

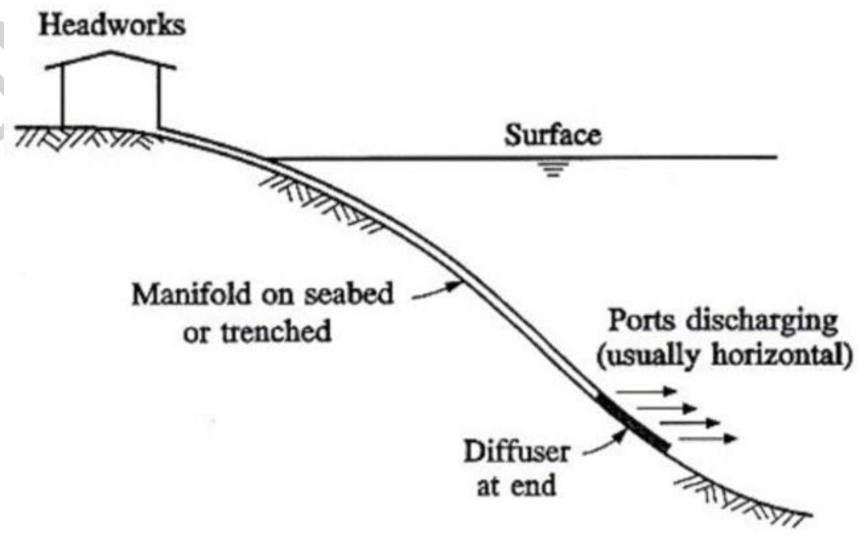


Figure 1. Typical arrangement for small outfall

The system would be designed to disperse the wastes widely through the receiving water and to ensure that organic matter is stabilized by natural processes without significantly lowering the quality of the receiving waters. Concentration of pathogens is reduced by dilution and natural die off (decay) and the outfall must be sited to ensure that coliform counts (an indicator of potential bacterial pathogens) are reduced to acceptable levels at sensitive points in the receiving waters (e.g., bathing beaches or shellfish nurseries).

Because natural assimilation of wastes takes place the system has been described as "marine treatment." This terminology may help to distinguish a well designed marine outfall from the discharge of raw sewage at, or just below, low water. Further details of outfall hydraulics, technical details and construction methods are available in various general bibliographical works (see *Storm Water Drainage and Effluent Disposal*).

Comparisons between the performance of land based secondary treatment plants and that of ocean outfalls are often made as if they were comparisons between "full" treatment and total lack of treatment. This approach to the problem is misleading and irrational because the primary difference between the two lies not in the manner of the treatment, but in the location of the treatment process.

In a secondary treatment plant, sewage wastes are reduced by the action of bacteria and other microorganisms in enclosed basins. In the sea the same result is obtained by essentially the same natural processes but the size of the treatment zone is increased, while the concentration of pollutants is reduced. One major difference is the degree of control exerted over the two types of treatment.

Purification in a treatment plant is closely controlled whereas the only control over marine treatment lies in the choice of the outfall site, the design of the outfall, and the permissible rate of loading. All other processes occur naturally following discharge. With proper design it is possible to ensure that the conversion of organic wastes occurs aerobically. Dilution is, of course, of great importance—not only does it decrease the concentration of wastes, it also, and more importantly, provides an abundant source of dissolved oxygen so that aerobic bacteria and other higher forms of life flourish without seriously depleting the dissolved oxygen concentration. Indeed, in a well managed system, the presence of an outfall can lead to higher productivity of commercial fishing (see *Commercial and Sport Fisheries*).

The technique could be compared with farmyard manure being thinly spread over fields in a well managed farm to increase crop production while the manure breaks down naturally. Similarly, a secondary treatment plant and subsequent sludge treatment could be compared with the same weight of manure being allowed to pile up in the farmyard pit. There it rots slowly and produces a liquid effluent which has a high concentration of readily assimilated nutrients.

Problems caused by the leaching of farmyard effluents to ponds and rivers are well known. It is obvious that the same quantity of waste must be treated and disposed of in each case. In the former however there can be considerable benefit when the waste is distributed widely. The second situation may require further costly treatment to minimize deleterious effects. In both cases it is essential to ensure that toxins and heavy metals, which might be concentrated in the food chain, are not present in the effluent at discharge (see *Effluents; Wastewater Treatment; Waste Disposal*).

2. Problems of Conventional Systems

It is often assumed that land based treatment provides a "pure" effluent with no side effects. Little could be further from the truth. Liquid wastes following treatment are usually rich in nutrients (chemical substances essential for plant growth, e.g., ammonia and nitrate nitrogen, and also phosphorus); they are often discharged to the sea, where the relatively clear outflow conceals the food immediately available for algae growth. "Natural" decay and organic detritus from algal blooms can pose significant detrimental environmental changes and olfactory and aesthetic values may be offended just as badly by decaying algae as by crude sewage.

For example, a population of 10 000 persons discharging 200 liters per person per day of effluent containing 15 mg L^{-1} N-$N0_3$ and 5 mg L^{-1} phosphorus will provide sufficient nutrients to produce between 475 and 1145 kg algae per day. Typical changes in a treatment plant are shown in Table 1 below:

Stage	5-day BOD (mg L^{-1})	Suspended solids (mg L^{-1})	Total coliform count per 100 ml
Raw sewage	220	220	10^8
At end of primary treatment	200	90	5×10^6
At end of secondary treatment	20	30	4×10^6
At end of tertiary treatment	12 to 15	12 to 15	2×10^6
After chlorination of secondary effluent			1×10^6

Table 1. Typical water quality changes in a treatment plant

The biochemical oxygen demand is reduced from about 220 mg L^{-1} (assuming an average strength domestic sewage) to about 20 mg L^{-1} after secondary treatment. Similar reductions occur in the suspended solids concentration. Bacterial counts in the effluent discharged from a secondary treatment plant are still far too high to meet statutory guidelines for bathing beaches (typically about 500 to 600 coliforms per 100 ml) without some form of sterilization being applied. If chlorination is used and the discharge is close to shellfish beds, then the dangers of residual chlorine and toxicity to spat or larvae must be dealt with.

Environmental concerns related to on-land treatment are often limited to water quality when comparisons are made with sea outfalls, but this gives a limited and misleading picture. In addition to the quality of the liquid effluent, consideration must be given to factors relating to land use, odor, and sludge disposal (see *Guidelines for Potable Water Purification*).

Secondary treatment can require an area of 5–8 × 10^3 m^2 for every 100 000 persons served by the sewer system, while with tertiary treatment, the figure can rise by a factor of 3 or 4. In a coastal situation, the hydraulic flows often dictate that the most desirable site is close to the beach if pumping is to be minimized. Land in this area is generally of high visibility and the development of a treatment plant could be visually offensive. There are also significant financial concerns. Because of its desirability, coastal land has the potential of generating high tax revenues which would not be available if the land were used for a municipal treatment plant. Odors are perhaps a minor problem but would often be judged unacceptable within 0.25 km, and unpleasant within 0.5 to 2.0 km on the downwind side.

Disposal of sludge may cause significant difficulties. Every 1000 m^3 per day of treated effluent generates 2.14 m^3 per day or 132 kg dry weight per day of sludge, which must be treated to varying degrees and then disposed of. It has been estimated that some 25% of the operating costs of treatment rests with sludge treatment and disposal. If chemical additives are used in the treatment, for example, in phosphorus removal, then the volume of sludge and the percentage cost is larger. Finding a suitable location for sludge disposal may also pose significant problems and some countries now use large-scale incineration (see *Urban Waste Disposal*).

These problems are exacerbated in small towns. There, the people generally have rural lifestyles, there is limited manufacturing, and in many cases toxins and heavy metals are not a concern. Little mechanical expertise is available and there is no significant pool of personnel with technical training or ability. The tax base is small and there is little finance available for the construction, operation or maintenance of treatment plants. Although government funds may be available for plant construction, operation and maintenance must usually be financed by the local municipalities.

Studies of rural communities on the East Coast of Canada provide examples. There, the combination of inadequate funding and a low level of technical expertise in rural areas has led in many cases to a severe reduction in plant efficiency within a few years of installation. Skilled labor is not available at the remuneration which can be afforded and little money is available for replacement of worn out parts. Instances have occurred where plants have been deliberately bypassed, with untreated sewage being discharged at the shoreline.

In a survey of various treatment plants in Eastern Canada it was found that the most important factor affecting the efficiency of plants was lack of operator attention—partly because of lack of training, but also because the operator was responsible for many other municipal matters. Most treatment plants are operated with low efficiencies—between 6% and 60%. Indeed, some plants were much worse, and instances were noted where the Biochemical Oxygen Demand of the effluent from the plant was higher than that of the influent. Sludge returns, which require extensive operator attention, were very prone to trouble, and in general, insufficient attention was given to sludge disposal.

Many problems were caused by simple lack of knowledge. In at least one case a municipality did not realize that sludge must be cleared out at regular intervals, with the result that the sludge built up until untreated sewage skated quickly over a deep bed and was discharged with virtually no treatment. Sporadic hydraulic loading, from schools and service stations, or hydraulic overloading due to excessive infiltration or illegal storm water connections, caused considerable trouble, particularly in the light of inadequate operator attention. Long delivery times for spare parts caused unacceptably long shut-down periods when maintenance and equipment replacement was needed. In some cases, parts were difficult to find and original suppliers had gone out of business. Financial demands on owners—usually small, limited budget townships—were excessive, and many owners did not budget adequately for the necessary equipment, supplies, utilities and manpower required for proper operation and maintenance (see *Mechanical and Electrical Equipment in Water Supply Projects*).

These problems related particularly to the smaller, more isolated, communities but were, and are, still apparent in many larger locations outside the major centers. Experience in other, similar, areas suggests that the situations described are not atypical for many rural areas around the world, although the severity with which the problems are experienced may be somewhat lessened by different administrative arrangements.

The important point of these descriptions of sewage treatment in remote coastal communities, is that environmental comparisons between marine outfalls and secondary treatment are quite unrealistic if the comparison does not take into account the fact that secondary treatment plants for small communities often do not work very well. It must also be realized that the very factors which militate against satisfactory operation of treatment plants—low funding for maintenance and operation combined with inadequate attention of untrained operators—are not particularly relevant for outfalls, which require little maintenance or operator attention.

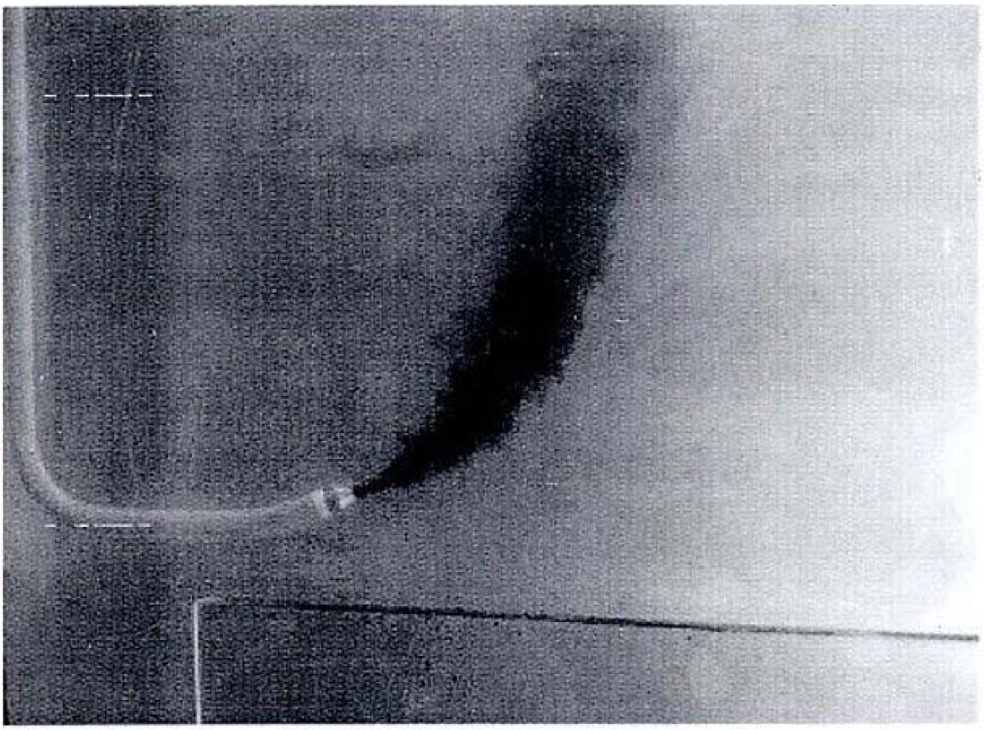
Comparisons have shown that outfalls could, in general, be designed so that they were no more hazardous to the environment than secondary treatment plants. In cases where the treatment plant is likely to operate at low efficiency, the outfall will probably be a more logical choice from an environmental viewpoint. Thus, in small nonindustrial communities, the quality of the environment around a marine outfall will almost certainly be better than that around a secondary treatment plant which is not functioning to its design specifications (see *Environmental Impact Studies in Hydraulic Engineering*).

3. Designing for Marine Treatment

Hydraulic design of an ocean outfall requires consideration of the mixing which occurs after discharge in order to calculate concentration of pollutants at various sensitive locations. The internal hydraulics of the outfall must also be considered. Here, emphasis will be on small outfalls which would typically be used in small coastal communities. In such cases it is likely that a desk top study using time tested empirical equations would be acceptable. Larger systems might require an in-depth study utilizing sophisticated two- or three-dimensional mathematical models (see *Hydraulic Methods and Modeling*).

3.1 Initial Dilution

Effluent is discharged from the end of the pipe as a jet with initial momentum. This gives rise to strong velocity gradients which cause mixing between the sewage and the receiving water. Because of the density difference between the jet and the receiving water (sewage typically has a density close to that of fresh water) the jet is also buoyant. The buoyant jet bends towards the vertical and rises to the surface (see Figure 2). The region in which this occurs is called the near field, and the dilution which occurs between the discharge port and the surface is known as the initial dilution. Dilution is defined as the ratio of the volume of effluent contained in a mixed volume of effluent and sea water. One volume of effluent mixed with ninety-nine volumes of sea water has a dilution of one hundred; conversely the concentration of a pollutant in the effluent is reduced by a hundred times.



Model of the Wah Fu Outfall, Hong Kong. This shows a single round, buoyant jet in still water. (F_o = 6.3, discharge angle = 20°)

Figure 2. Model of the Wah Fu Outfall, Hong Kong

Figure 3 shows a schematic diagram of a submerged single port outfall. This may simply be the open end of a pipe laid on the sea floor or one of a series of holes drilled into the side of a multi-port diffuser. Provided the jet Reynolds number u_oD/v (where u_o = jet discharge velocity, D = port diameter, and ν = kinematic viscosity) exceeds about 2000 - a condition that is always met in practice - the flow will be turbulent (see *Fluid Mechanics*).

The jet trajectory, concentration and the velocity field are governed by two important non-dimensional parameters: the densimetric Froude number, F_o, which is the ratio of inertia to buoyancy forces, and the relative depth, Z/D (Z = vertical distance above jet discharge point and other variables are defined following Equation 1). For $F_o \sim 1$, the discharge behaves like a source of pure buoyancy (plume) and for $F_o \sim \infty$ the discharge resembles a pure momentum jet—i.e. a jet with no buoyancy. In a buoyant jet the flow is jet-like near the discharge port and plume-like at large values of *Z/D* where the source kinetic energy has been dissipated.

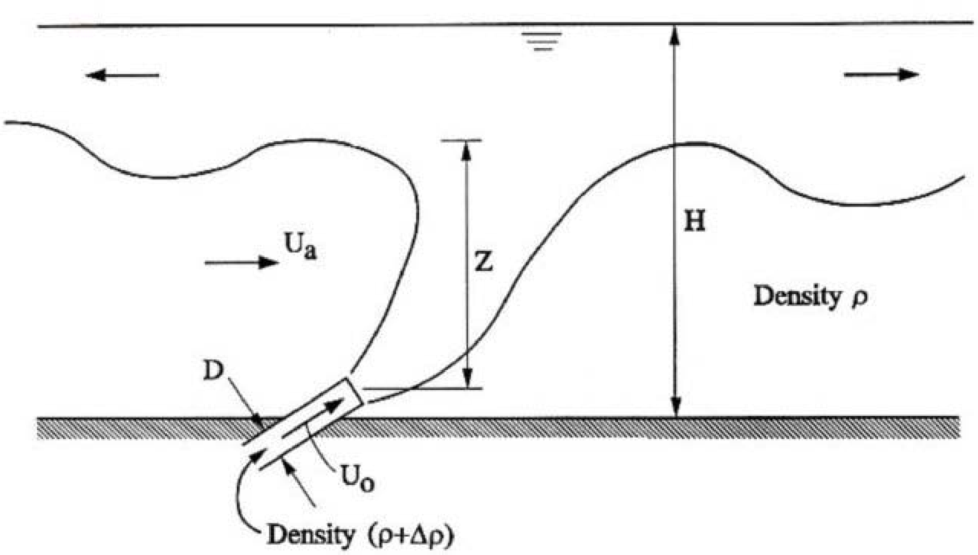


Figure 3. Submerged buoyant jet discharging into water of finite depth

Figure 2 shows an example of a buoyant jet discharge in otherwise still water observed in a laboratory model of a coastal outfall. It can be seen the discharge is initially jet-like with a straight trajectory, and curves upwards due to buoyancy after a certain distance. As the dyed effluent jet mixes with the surrounding fluid by a process known as turbulent entrainment, the width of the mixed fluid (the dyed jet) grows rapidly along with a corresponding reduction of concentration.

Figures 2 and 3 both show what is known as a deep water condition, in which a distinct buoyant jet rises to the surface and dilution occurs because of turbulent jet entrainment. Under shallow water conditions, however, instabilities may arise if the discharge momentum is sufficiently strong to cause a dynamic breakdown of the buoyant jet motion, and to form a local recirculation zone. Instability may be prevented if the inequality in Equation (1) below holds:

$$H / D \rangle 0.22 F_0 \qquad (1)$$

where H = depth of receiving water, D = diameter of jet and F_o is the densimetric Froude number, which is given by Equation (1a):

$$F_o = u_o/(g'D)^{0.5} \qquad (1a)$$

where u_o is the velocity of the jet and g' is the reduced gravitational acceleration given by $g' = g\Delta\rho/\rho$ in which ρ is the density of the receiving water and Δρ is the density difference between the effluent and the receiving water at point of discharge.

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Biographical Sketches

Jim Sharp has the degrees B.Sc., M.Sc., ARCST, Ph.D., and the Professional Status of P. Eng., C. Eng. He is a Fellow of the Canadian Society for Civil Engineering, the Institution of Civil Engineers (UK) and the Engineering Institute of Canada. He is Professor of Engineering in the Faculty of Engineering and Applied Science at the Memorial University of Newfoundland, Canada, where he was Associate Dean (1992–1998) and Chairman of Civil Engineering (1983–1991). He has more than thirty years of experience in higher education, including positions of academic leadership. His research and teaching interests relate to hydrotechnical and environmental engineering. He has published four hydro-technical books and more than one hundred papers and articles on research topics. He acts as a reviewer for scholarly journals and as a consultant for engineering firms in Newfoundland. He has written widely on educational matters and has other academic interests, having published two history books and a number of trade books. In 1991 he was honored by the Canadian Society of Civil Engineers with the Dagenais Award for outstanding contributions to the development and practice of hydrotechnical engineering in Canada. In 1993 he received the ASCE Award for the best technical note (Hydraulics) in the previous year, and in 1996 the Newfoundland Association of Professional Engineers and Geo-scientists Award for important and valued contributions to the profession of engineering and to Newfoundland and Labrador. In 1998 he received the James A. Vance Award for outstanding service to the Canadian Society for Civil Engineering, and in 1999 the Award for Research Excellence from the Environmental Protection Agency of China. His experience includes two and a half years of professional work in Africa, and visiting professorships at Universities in Singapore, Hong-Kong, West Malaysia, Sarawak and the United Kingdom. Since 1992 he has been external advisor and assessor to the Civil Engineering Department at the University of Malaya in Kuala Lumpur, and he is currently also a member of the Editorial Board for the Journal of that University. In 1994 he was made an Honorary Professor of Shandong University of Technology, China. He has worked as an educational consultant in the Philippines where he advised on accreditation procedures and on the development of engineering curricula for the country. He has also been involved in the accreditation of Canadian Universities and Government Research Organizations. His current research interests relate to the hydraulics of ocean outfall structures, a research area funded by the Natural Sciences and Research Council of Canada.

Joseph Hun-Wei Lee is Redmond Professor of Civil Engineering and Associate Dean of the Faculty of Engineering, Hong Kong University, Hong Kong, China. He holds the degrees B.Sc. (1973), M.Sc. (1974) and Ph.D. (1977) all from the Massachusetts Institute of Technology (MIT), USA. Before joining the University of Hong-Kong in 1980, he was Assistant Professor at the University of Delaware for three years. He is an internationally recognized expert in hydraulic and environmental engineering. He is Chairman of the Fluid Mechanics Section of the IAHR and Associate Editor of the Journal of Hydraulic Engineering of the ASCE, of Water Quality and Ecosystem Modeling, and of China Ocean Engineering. He has published more than one hundred articles in international journals and conference proceedings. He was awarded the Alexander Von Humboldt Research Fellowship by the German Government in 1991, and the Croucher Foundation Senior Research Fellowship in 1998 for his contributions to the theory of buoyant jets. He is Consulting Professor at Tongji, Hohai and Beijing Normal Universities. Over the past two decades he has served as expert advisor to international consultants and the Hong-Kong Government on a number of local and overseas projects, including UK Marine Out-fall Design Guide, Sydney Deep-water Out-fall Study, Shanghai and Hong-Kong Sewerage Disposal Projects, River Indus Flooding Study, Water Quality and Red-tide Monitoring Studies. He served on the Hong-Kong Research Grants Council Panel and is Chairman of the Hong-Kong University Grants Committee Panel.