Mixing Zone Regulations for Marine Outfall Systems

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Abstract
Environmental standards and their implementation to marine wastewater discharges in different countries are reviewed. Effluent standards alone, or mandating specific levels of wastewater treatment, can result in poor choice of treatment and outfall, waste of resources, and unnecessary expense. The combined application of ambient and effluent standards requires mixing zone regulations. Recommendations are given on procedures to establish environmental standards and related mixing zone definitions. A case study of dilution calculations for a mixing zone permit is given for the San Francisco ocean outfall which illustrates the need for careful definitions of the quantities involved. Design recommendations are given on how to plan, design, and locate marine outfalls. We recommend adoption of mixing zones in countries that do not have them as a practical means of ensuring environmental protection at reasonable cost.

Keywords
environmental standards, water quality, discharge, diffuser

INTRODUCTION

Marine outfalls can be an effective, reliable, and economical solution to wastewater disposal that have minimal environmental impacts. They are *point sources* that avoid the water quality problems in urban coastal regions which are often directly related to badly positioned or uncontrolled discharges. This is especially true for megacities (e.g. Rio de Janeiro, Istanbul, Mumbai, Hong Kong), densely populated or popular tourist regions (e.g. Spanish Mediterranean coast), or regions with poor infrastructure (e.g. developing countries). There, point sources may contribute significant bacterial contamination (IETC, 2000) causing considerable public health impacts and environmental degradation (UNEP, 2004). They originate mainly from municipal wastewater systems and stormwater overflows, but also from industrial facilities. These discharges span a huge range of flows and size of the installed facilities.

Diffuse sources, originating mainly from surface runoff, often dominate water quality problems in rural and agricultural regions or environmentally sensitive waters with weak flushing characteristics (e.g. mangrove forests at Paranaguá, Brazil or Wadden Sea at the northern German coast). Their impacts are related mainly to ecosystem damage and less to public health impacts (e.g. bacteria and algal blooms). Controlling diffuse sources is challenging and difficult and depends on long-term administrative control mechanisms rather than engineering solutions. Therefore, this paper will focus on point-sources.

Water quality problems from point source discharges can arise if the capacity of the receiving waters to assimilate the introduced substances is exceeded. Pollution is caused by exceeding critical assimilation time scales (too much substance in a too short time), and length scales (too much substance at one location). Engineering actions are then required to reduce contaminant concentrations in the receiving water body by a combination of reducing the substance loads (wastewater treatment) and improving the substance dispersion (effective outfalls).

A typical engineering system or marine wastewater disposal scheme is shown schematically in Figure 1. It usually consists of a wastewater treatment plant and a discharge structure - the outfall.

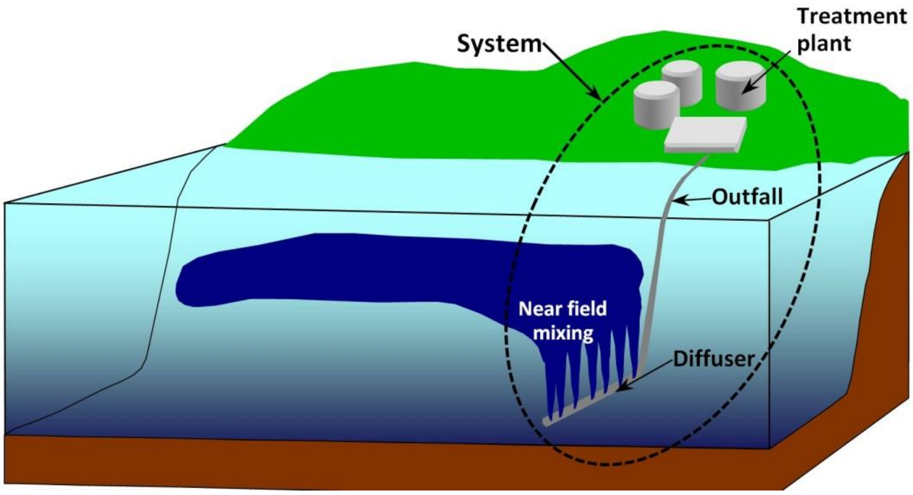

Figure 1. A marine wastewater disposal system: Treatment plant, outfall pipe, diffuser, and near field (Roberts et al., 2010)

The outfall is a pipeline or tunnel, or combination of the two, which terminates in a diffuser that efficiently mixes the effluent in the receiving water. The size of these schemes vary widely, but the outfalls typically range from 1 to 4 km long and discharge into waters 20 to 70 m deep. Some may lie outside these ranges, for example lengths of 500 m or less and discharge depths of 150 m or more when the seabed slope is very steep, or lengths of more than 5 km when the slope is very gradual. The disposal system can be thought of as the treatment plant, outfall, diffuser, and also the region round the diffuser (known as the near field) where rapid mixing and dilution occurs. There is often a misconception that treatment results in a "pure" and "clean" effluent which often leads to underutilization of outfall technologies. Conversely, highly efficient outfalls without treatment do not necessarily eliminate pollution because of their unchanged mass emission rates. Consequences of both extremes are inefficient or overly expensive wastewater systems with ongoing water quality problems (UNEP, 2002).

This paper summarizes existing environmental protection philosophies and related standards for marine outfall systems and offers recommendations for further amendments and design improvements.

DISCHARGE CHARACTERISTICS AND MIXING PROCESSES

The discharge characteristics are defined by 1) the discharge structure itself, such as its type (open channel, submerged/elevated pipe, etc.), the discharge site (at the bank, in the water body, in the bay, close to breakwaters or groynes, etc.), the dimensions of the discharge structure (channel cross-section, pipe diameter, multiport diffuser, etc.), the orientation of the discharge structure to prevailing currents or dominant geographical/bathymetrical features, and 2) the effluent, such as its type, physical properties (temperature, salinity, density, etc.), flow rate, chemical and biological characteristics (concentrations of toxics and bacteria, suspended solids, oxygen demand, etc.), and the mass emission rates of various contaminants.

The receiving water characteristics are defined by 1) local conditions near the discharge site, such as the type of water body (deep ocean, coastal, estuary, etc.), the topography (enclosed bay, straight coastline, lagoon, etc.), the bathymetry (seabed slopes, etc.), the physical properties (temperature, salinity, density, current speeds, etc.), the meteorological and hydrological conditions (velocity and water level variations, density variations, tidal flows, etc.), the chemical and biological properties (background concentrations, water quality conditions, natural assimilation capacities, etc.), and 2) the regional conditions for the whole water body or parts of it, such as proximity to other environmental stresses (other discharges, morphological changes, dams, backwaters, etc.), proximity to sensitive aquatic ecosystems (mangrove forests, salt marshes, coral reefs, or low energy intertidal areas and shallow coasts), and the general flushing characteristics (residence and exchange times).

Marine wastewater discharges through outfalls have unique characteristics that are shown in Figure 1. The wastewater is usually ejected horizontally as round turbulent jets from a multiport diffuser. The ports may be spaced uniformly along both sides of the diffuser or clustered in risers attached to the outfall pipe.

Buoyancy and oceanic density stratification play fundamental roles in determining the fate and transport of marine discharges. Because the density of domestic sewage is close to that of fresh water, it is very buoyant in seawater. The jets therefore begin rising to the surface and may merge with their neighbors as they rise. The turbulence and entrainment induced by the jets causes rapid mixing and dilution. The region in which this occurs is called the "near field." If the water is deep enough, oceanic density stratification may trap the rising plumes below the water surface; they stop rising and begin to spread laterally. The wastefield then drifts with the ocean current and is diffused by oceanic turbulence in a region called the "far field." The rate of mixing, or increase of dilution, is much slower in the far field than in the near field. As the wastefield drifts, particles may deposit on the ocean floor and floatables may reach the ocean surface to be transported by wind and currents. Finally, large scale flushing and chemical and biological decay processes removes contaminants and prevents long-term accumulation of pollutants.

The mixing performance is usually expressed by a dilution value, which is a measure of contaminant concentration reduction. It is generally defined as the reciprocal of the volume fraction of effluent in a sample (i.e. total sample volume ÷ volume of effluent in the sample). Dilutions achieved within the near field are typically of the order of hundreds to even thousands to one. Multiport diffuser outfalls are efficient mixing devices and if they are located in regions with high transport and assimilative capacities they can have minimal environmental impacts.

The fate and transport of discharged effluents is influenced by processes that operate over a wide range of length and time scales. The orders of magnitude of these processes are illustrated in Figure 2, being of the order of tens of meters and minutes for the near-field and kilometers and hours for the far-field. The "near-field" is governed by the initial jet discharge momentum and buoyancy fluxes and outfall geometry which influence the effluent trajectory and mixing. Outfall designers can usually affect the initial mixing characteristics through appropriate manipulation of design variables, thus influencing effects within the near-field region. In the "far-field", ambient conditions control plume trajectory and dilution through buoyant spreading motions and density currents, passive diffusion, and advection by the usually time-varying velocity field.

Predicting these processes is difficult because oceanic conditions vary widely in space and time, resulting in considerable spatial variability and heterogeneities and strong temporal variability in the near and far fields. This has significant implications for the application of water quality standards and monitoring and definitions of mixing zones as discussed below.

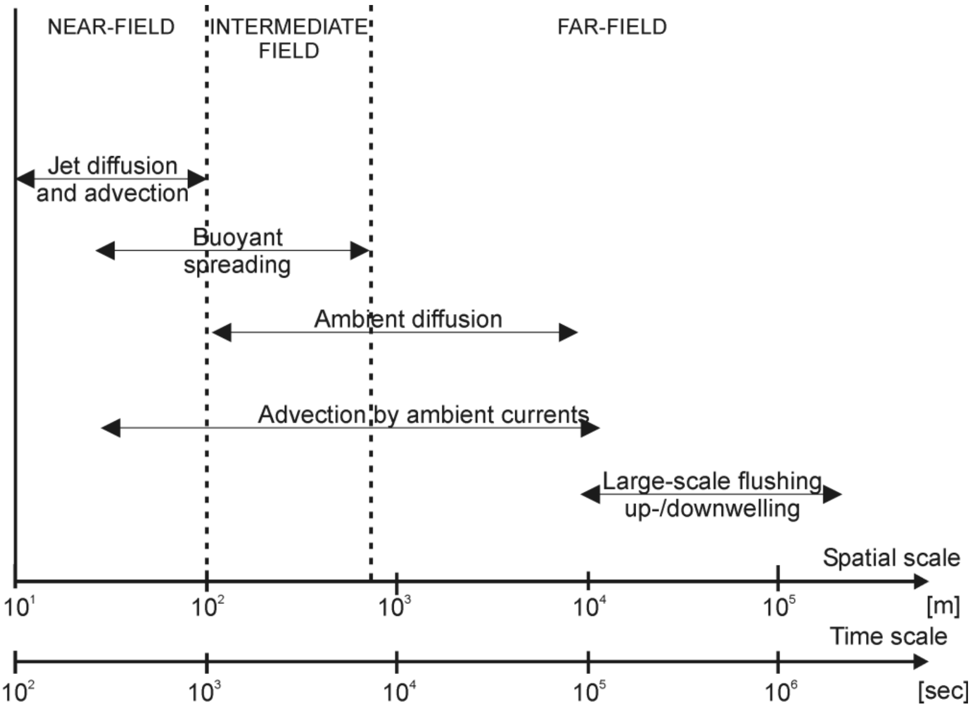

Figure 2. Typical temporal and spatial scales for transport and mixing processes related to coastal discharges (Jirka et al., 1976, Fischer et al., 1979)

ENVIRONMENTAL STANDARDS

Point sources are usually controlled by setting environmental standards. The most common standards are Effluent Standards (ES), called emission limit values in European regulations, and Ambient Standards (AS), called environmental quality standards in European regulations. AS are water quality standards, applicable to the receiving water body. There are different philosophies in applying either one or a combination of both of these standards for pollution management, as discussed below.

ES encourage source control, such as effluent treatment and recycling. AS require consideration of the environmental response and are often associated with the concept of a "mixing zone," an allocated impact zone in which the numerical water quality standards can be exceeded (Jirka et al., 2004a,b).

ES are preferred from an administrative perspective because they are easy to prescribe and to monitor (end-of-pipe sampling). ES are usually set as limiting concentration values for pollutants or minimum required treatment levels. From an environmental perspective, however, a control based on ES alone appears illogical, since it does not directly consider the actual impacts on the water body and therefore does not hold the discharger responsible for it. Consider for example a large point source on a small water body or several sources that may all individually meet the ES but would cumulatively cause excessive pollutant loading.

The National Research Council of the US National Academy in its major study *Managing Wastewater in Coastal Urban Areas* (NRC, 1993) specifically recommended against a "one size fits all" approach to arbitrary specification of treatment levels, stating:
"Coastal wastewater and stormwater management strategies should be tailored to the characteristics, values, and uses of the particular receiving environment based on a determination of what combination of control measures can effectively achieve water and sediment quality

objectives," and "Coastal municipal wastewater treatment requirements should be established through an integrated process on the basis of environmental quality as described, for example, by water and sediment quality criteria and standards, rather than by technology-based regulations."

The requirement of treatment to arbitrary levels beyond these can waste scarce financial resources, require excessive energy use, and generate large quantities of sludge that must be disposed of on land.

AS are usually set as concentration values for pollutants in the receiving water or maximum loads (e.g. the "total maximum daily load, TMDL" approach in the USA), that may not be exceeded in the water body. They have the advantage that they directly consider physical, chemical and biological impacts due to the discharge and therefore put the direct responsibility for receiving water quality on the discharger. But this presents the regulatory authorities with additional burdens because of more difficult monitoring – where in the water body and how often should water quality be measured? – for existing discharges or require predictive modelling for new discharges. A "combined approach," as for example described in the European Water Framework Directive, WFD (EC, 2000), combines the advantages of both of these water quality control mechanisms. Both criteria must be met for a discharge permit. Concentration or load limits for ES and AS can be found in state, national, and international legislations for different substances, effluents, and receiving water characteristics.

Some examples for ES and AS for various pollutants are given in Table 1. The ratio ES/AS is often approximately 100, and generally within a range of 5 to 1000 for most chemical and physical parameters, such as temperature. This ratio describes the impact of the pollutants on the ecosystem, since the ES is considered to protect against acute (lethal) effects on organisms, while the AS is supposed to prevent long-time chronic influences.

Table 1: Examples for emission limit values (ELV) and environmental quality standards (EQS) for two selected pollutants

Pollutant example	Emission standard ES	Ambient standard AS	ES/AS
Copper	500 µg/l (Worldbank, 1998)	4.8 µg/l (USEPA, 2006)	104
Chlorine	200 µg/l (Worldbank, 1998)	7.5 µg/l (USEPA, 2006)	27
Bacteria	WHO, California, EC	WHO, California, EC	
Temperature	10 above ambient (Worldbank, 1998)	3 above ambient (Worldbank, 1998)	3

Another approach is shown in Table 2 which is "Table B" of the California Ocean Plan (SWRCB, 2005). It contains numerical water quality objectives for the protection of aquatic life. It specifies three different limiting concentrations: a 6-month median, a daily maximum, and an instantaneous maximum. The instantaneous values are intended to protect against acute impacts, and the time-average values against chronic effects. It is important to note that these limits are specified *at the completion of initial dilution* according to the following equation:

$$C_e = C_o + D_m(C_o - C_s) \quad (1)$$

where C_e is the effluent concentration limit, C_o is the concentration to be met at the completion of initial dilution (the water quality objective), D_m is the minimum probable initial dilution, and C_s is the background seawater concentration. Minimum initial dilution is defined as:

"...the lowest average initial dilution within any single month of the year. Dilution estimates shall be based on observed waste flow characteristics, observed receiving water density structure, and the assumption that no currents, of sufficient strength to influence the initial dilution process, flow

across the discharge structure."

Table 2. *"Table B" of the California Ocean Plan: Water Quality Objectives for Protection of Marine Aquatic Life*

Compound	***Limiting Concentrations***			
	Units	***6-Month Median***	***Daily Maximum***	***Instantaneous Maximum***
Arsenic	*µg/l*	*8.*	*32.*	*80.*
Cadmium	*µg/l*	*1.*	*4.*	*10.*
Chromium (Hexavalent)	*µg/l*	*2.*	*8.*	*20.*
Copper	*µg/l*	*3.*	*12.*	*30.*
Lead	*µg/l*	*2.*	*8.*	*20.*
Mercury	*µg/l*	*0.04*	*0.16*	*0.4*
Nickel	*µg/l*	*5.*	*20.*	*50.*
Selenium	*µg/l*	*15.*	*60.*	*150.*
Silver	*µg/l*	*0.7*	*2.8*	*7.*
Zinc	*µg/l*	*20.*	*80.*	*200.*
Cyanide	*µg/l*	*1.*	*4.*	*10.*
Total Chlorine Residual	*µg/l*	*2.*	*8.*	*60.*
Ammonia (as nitrogen)	*µg/l*	*600.*	*2400.*	*6000.*
Acute Toxicity*	*TUa*	*N/A*	*0.3*	*N/A*
Chronic Toxicity*	*TUc*	*N/A*	*1.*	*N/A*
Phenolic Compounds (non-chlorinated)	*µg/l*	*30.*	*120.*	*300.*
Chlorinated Phenolics	*µg/l*	*1.*	*4.*	*10.*
Endosulfan	*µg/l*	*0.009*	*0.018*	*0.027*
Endrin	*µg/l*	*0.002*	*0.004*	*0.006*
*HCH**	*µg/l*	*0.004*	*0.008*	*0.012*
Radioactivity	*Not to exceed limits specified in Title 17, Division 1, Chapter 5, Subchapter 4, Group 3, Article 3, Section 30253 of the California Code of Regulations. Reference to Section 30253 is prospective, including future changes to any incorporated provisions of federal law, as the changes take effect.*			

Background levels for arsenic, copper, mercury, silver, and zinc are specified in the ocean plan; the background levels of all other constituents are assumed to be zero.

These examples illustrate that environmental protection measures should be based on local and regional objectives, and cannot be generalized. Standards are usually set by environmental agencies based on ecotoxicological measurements in the field and the laboratory. These tests expose regionally occurring species to different pollutants and concentrations under local climate and water body conditions and natural background concentrations.

It is more difficult to set standards for public health protection (Kay et al., 2004). There are still numerous outfalls where critical faecal indicator bacteria concentrations are used as the *only* design criteria. And often the commonly used WHO standard (World Health Organization, 2003) is used without regional validation. However, as has been said for polluting substances and their ecotoxicological effect and related standards, there can be significant regional variations to the applicability of general international standards. In particular, standards for faecal indicator bacteria must be handled carefully and never without extensive regional field measurements. There are numerous sources for faecal indicator bacteria and numerous parameters that influence the inactivation of indicators in coastal waters. Nevertheless, outfall designs are usually optimized to minimize public health impacts. This is accomplished mainly by designing and siting the outfall to decrease bacteria concentrations and to avoid the transport of effluents to sensitive regions (i.e. beaches). Generally, bacterial standards apply at regions of recreational water use, such as at beaches and the shoreline. They are not usually specified in mixing zones as there they cannot be achieved by dilution alone only by advanced treatment and probably chlorination. Therefore, as this paper is concerned mainly with mixing zone regulations, we do not consider bacterial impacts further.

MIXING ZONE REGULATIONS

The rapid and very substantial contaminant reduction that occurs in the near field is recognized by the concept of a regulatory mixing zone. The mixing zone may not correspond to actual physical mixing processes, however. It may fully encompass the near field and extend some distance into the far field, or it may not even fully contain the near field. Mixing zones can be defined as lengths, areas, or water volumes.

The ratio ES/AS of the listed concentration limits in Table 1 also expresses the dilution that must be attained through physical mixing, or - to some extent - through biological decay and chemical transformations. Usually a regulatory mixing zone concept is applied to delimit the mixing region to avoid concentrated plumes extending long distances or impacts with nearby sensitive regions.

Modern water quality regulations, such as the European Water Framework Directive, WFD, (EC, 2000, 2008) include statements such as: *"Member States may designate mixing zones adjacent to points of discharge. Concentrations of one or more substances listed in Part A of Annex I may exceed the relevant AS within such mixing zones if they do not affect the compliance of the rest of the body of surface water with those standards."*

Criteria for the spatial location and extent of the mixing zones are hereby defined (EC, 2008, Article 4, (3)): They should be (a) restricted to the proximity of the point of discharge; (b) proportionate, having regard to the concentrations of pollutants at the point of discharge and to the conditions on emissions of pollutants contained in the prior regulations, …

The mixing zone defined above is a regulatory formulation with the following general attributes: 1) The term "mixing zone" signifies explicitly that mixing processes require a certain spatial extent within which mixing processes operate. 2) The term "restricted" should guarantee that the mixing zone shall be minimized by the regulatory authority for the purpose of attaining the environmental quality goals. 3) While the mixing zone includes a portion - namely the initial one - of the actual physical mixing processes, these processes will continue beyond the mixing zone where they lead to further concentration reductions in the pollutant plume below the AS-values. 4) The definition is restricted to "point sources" since diffuse sources usually do not contain such clearly distinct mixing processes.

There are various definitions of mixing zones used by different countries around the world, and even within one country there may be multiple definitions. For example, in the United States, the EPA regulations for toxics (USEPA, 1991), defines a mixing zone as:
"An area where an effluent discharge undergoes initial dilution and is extended to cover the secondary mixing in the ambient water body. A mixing zone is an allocated impact zone where water quality criteria can be exceeded as long as acutely toxic conditions are prevented." (Water quality criteria must be met at the edge of a mixing zone.)

There is similar language in the guidelines for the US National Pollutant Discharge Elimination System (NPDES) permits for the discharge of pollutants from a point source into the oceans at 40 CFR 125.121(c). This defines a mixing zone as a limited area where initial dilution takes place and where numeric water quality criteria can be exceeded but acutely toxic conditions are prevented. The dilution factor must be met at the edge of the mixing zone, and so depends on the dimensions of the mixing zone. The *Ocean Discharge Criteria* defines the mixing zone for federal waters as:
"...the zone extending from the sea's surface to seabed and extending laterally to a distance of 100 meters in all directions from the discharge point(s) or to the boundary of the zone of initial dilution as calculated by a plume model approved by the director, whichever is greater, unless the director determines that the more restrictive mixing zone or another definition of the mixing zone is more appropriate for a specific discharge."

The *Ocean Discharge Criteria*, and also the EPA 301(h) regulations (USEPA, 1994) refer to initial dilution. In the 301(h) regulations the *Zone of Initial Dilution (ZID)* extends to a fixed distance (equal to the water depth) from the diffuser. It is therefore a regulatory mixing zone. But the *Ocean Discharge Criteria* also refer to "...the boundary of the zone of initial dilution *as calculated by a plume model*" implying that it is a hydrodynamic mixing zone.

The U.S. EPA maintains two water quality criteria for toxic substances (USEPA, 1991). The CMC (Criteria Maximum Concentration) is for protection of the aquatic ecosystem from acute or lethal effects; the CCC (Criteria Continuous Concentration) is for protection from chronic effects. The CCC is like a regular water quality standard and must be met at the edge of the mixing zone. It is *"...intended to be the highest concentration that could be maintained indefinitely in a receiving water without causing an unacceptable effect on the aquatic community or its uses".* The CCC limits may be sometimes exceeded, as organisms can tolerate higher concentrations for short periods so long as peak concentrations are limited. In other words, the CCC relates to average concentrations which are in turn related to time-averaged dilutions. It is assumed that the CCC are the appropriate water quality criteria to apply to the outfall to protect the aquatic ecosystem from chronic effects.

The California Ocean Plan defines initial dilution (which is therefore a regulatory mixing zone) as:
"...the process which results in the rapid and irreversible turbulent mixing of wastewater with ocean water around the point of discharge. For a submerged buoyant discharge, characteristic of most municipal and industrial wastes that are released from the submarine outfalls, the momentum of the discharge and its initial buoyancy act together to produce turbulent mixing. Initial dilution in this case is completed when the diluting wastewater ceases to rise in the water column and first begins to spread horizontally." Further: *"The mixing zone for the acute toxicity objective shall be ten percent (10%) of the distance from the edge of the outfall structure to the edge of the chronic mixing zone (zone of initial dilution). There is no vertical limitation on this zone. The effluent*

limitation for the acute toxicity objective listed in Table B shall be determined through the use of the following equation:

$$C_e = C_a + (0.1) D_m (C_a) \quad (2)$$

where C_a *= the concentration (water quality objective) to be met at the edge of the acute mixing zone.* D_m *= minimum probable initial dilution expressed as parts seawater per part wastewater (This equation applies only when* $D_m > 24$*).”*

Mixing zone water quality standards are sometimes determined by bioassays and are usually limited to parameters for acute toxicity protection (such as Table 2) and to minimize visual impacts. They are not usually applied to BOD, dissolved oxygen, or nutrients. Bacterial standards are also not normally imposed within or at the boundary of mixing zones unless the diffuser is located near areas of shellfish harvesting or recreational uses.

The concept of a regulatory mixing zone is not new in an international context, and can be found in the water quality regulations of several countries. However, it is a new concept for many countries, where the ES approach alone has mainly been applied. The additional application of the AS promises further water quality improvements, if applied properly. However, there are authorities in countries with modern regulations that are reluctant to undertake the additional work needed to implement the mixing zone concept. Their arguments are often related to the difficulties in defining mixing zones and applying them. Below we show that very simple approaches exist to define mixing zones and standards and to demonstrate and prove compliance.

Figure 3 shows the most common definition of regulatory mixing zones for coastal discharges. As described in the previous sections it seems advisable to constrain the regulatory mixing zone to a limited region around the outfall in which the initial mixing processes (namely buoyant jet mixing) are dominant. In that fashion, and assuming a proper outfall design, the AS-values can be achieved within short distances. Thus the following specification appears effective for coastal discharges: *“The mixing zone is a volume with vertical boundaries that extend through the water column that is limited in its horizontal extent to a distance* D_{MZ} *equal to N multiples of the average water depth* H_{ave} *at the outfall location and measured in any direction from the outfall structure.”*

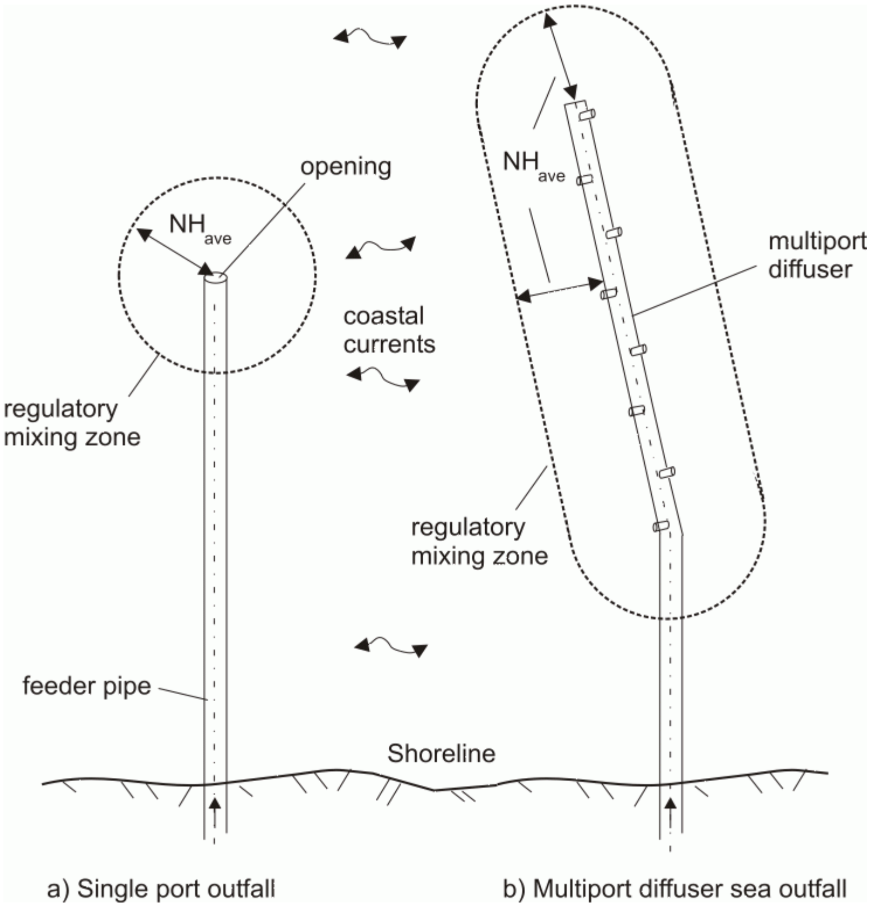

Figure 3: Examples of regulatory mixing zone specifications for offshore submerged coastal discharges (a and b) where the horizontal extent of the mixing zone is defined by some multiple N of the average water depth H_{ave} at the sea outfall.

The mixing zone definition in the above statement is a regulatory formulation with the following general attributes: 1) It results in a cylindrical volume with the port in its center (Figure 3a) for a single port outfall. For a multiport diffuser outfall with many ports arranged along a straight diffuser line it would be a rectangular prismatic volume with attached semicircular cylinders at the diffuser ends located along the diffuser line (Figure 3b). For diffusers with a curved diffuser line or piecewise linear sections the volume would follow the diffuser line. 2) It accounts for the typical scales of initial mixing processes, where the local water depth at the discharge location can be a major parameter limiting those processes. Thus discharges in deep waters have larger mixing zones, because of their better mixing characteristics. Therefore shoreline discharges (H_{ave} = 0) result in D_{MZ} = 0, would need a high level of treatment to achieve the AS directly at the discharge location. This is justified by the low dilution and very slow mixing of shoreline discharges, and proximity of sensitive locations, such as recreational beaches. It also follows the philosophy of completely avoiding shoreline discharges. 3) The multiplier N accounts for physical, chemical, and biological characteristics of the receiving waters, and/or effluent characteristics. The value N would typically be in the range of at least 1 to about 10 and set by the regulatory authority. For highly sensitive waters the minimum of 1 should be set. Common values for most coastal waters might be N = 2 to 3. The U.S. EPA 301(h) regulations previously discussed corresponds to N = 1.

Some guidance on how to specify the value of N is given below. The chosen value of N can account for different effluent types and receiving water characteristics. A different value of N can be defined for each discharged substance, based on factors like biodegradability, decay coefficients, or the ES/AS ratio. Different receiving water characteristics can be accounted for by using existing water quality parameters to describe the susceptibility and vulnerability of the ecosystem, the assimilative capacities, and other environmental stresses. Finally, the lowest *N* value is chosen because usually only one mixing zone size is defined for a specific location. An exception is the US regulations, where two mixing zones are defined for discharges that also contain toxic substances. For these cases another, much smaller toxic discharge zone is defined where toxic AS must be met outside that toxic mixing zone.

Another approach has been proposed in Spain (Freire, 2008) to compute the values for *N* based on sediment characteristics (hard substrates, mixed substrates and soft substrates) and ecological parameters (susceptibility, biotope protection status, biotope conservation status, and biotope sensitivity). Those values depend strongly on available data and can have unique values for a particular case. The combination of the values result in a single numeric value for *N*. Freire (2008) showed the applicability of that approach to three case studies of discharges into the Mediterranean and Atlantic coast.

In addition, mixing zone dimensions can be specified in an ad-hoc manner. Following prior ecological evaluations or predictions the discharger can request authority for a mixing zone with a certain dimension by showing that this would guarantee an integrated water quality protection. Based on its own examinations the authority can agree with that proposal or else demand further restrictions.

Mixing zone regulations should furthermore include statements like the following:
Though AS can be exceeded within the mixing zone the following discharges are not allowed: substances in concentrations that could form objectionable deposits, floating debris, oil, scum, or which produce objectionable colour, odour, taste or turbidity, or which produce undesirable aquatic life or dominance of nuisance species, or which result in acutely lethal toxic conditions to aquatic life or irreparable environmental damage including risk to ecosystem integrity and human health or which interfere with common water quality objectives. Mixing zones of different discharges may not overlap. Mixing zones may not interfere with natural and human recognized uses, such as water supply, recreational, fishing, aquaculture, nature conservation or other water uses.

Some similar statements are given in the California Ocean Plan, such as:
…there be no visible floating particulates and oil and grease, no aesthetically undesirable discoloration of the ocean surface, and natural light should not be significantly reduced outside the initial dilution zone.
And…control of chemical substances specify that:
The dissolved oxygen concentration shall not at any time be depressed more than 10 percent from that which occurs naturally;
The pH shall not be changed at any time more than 0.2 units from that which occurs naturally;
The dissolved sulfide concentration of waters in and near sediments shall not be significantly increased above natural conditions;
The concentration of substances set forth in Table B, in marine sediments shall not be increased to levels which would degrade indigenous biota;
The concentration of organic materials in marine sediments shall not be increased to levels that would degrade marine life;
Nutrient materials shall not cause objectionable aquatic growths or degrade indigenous biota.

EXAMPLE

Although the regulations shown above can be quite detailed, they do not usually specify exactly how dilution calculations are to be done, so considerable judgment is needed to decide which oceanographic conditions, density stratification, flow rates, and averaging times, etc. are used. They must be carefully chosen and explicitly specified. To illustrate the difficulties and issues involved, an example is given below of calculations of dilution for issuance of a discharge permit for the San Francisco ocean outfall.

Introduction

The San Francisco outfall is shown in Figure 4. It is 7.2 km long and carries treated wastewater out to a diffuser system that begins 6.1 km from shore at a depth of 23.8 m. The diffuser is 922 m long and consists of 85 risers spaced 11.0 m apart; each riser contains eight ports with nominal diameters of 109 mm. The hydraulic design capacity of the outfall is approximately 20 m^3/s in order to convey the dry weather flows from the entire city. At present, however, the average dry weather flow is only about 0.8 m^3/s, approximately 4% of capacity. Therefore, to maintain adequate port velocity to prevent seawater intrusion, only 21 out of the 85 risers are currently open. The 21 active risers begin from the offshore end and alternate, so the effective riser spacing is 21.9 m; only 12 of these risers are actually discharging, however, so the effective diffuser length was assumed to be 241 m.

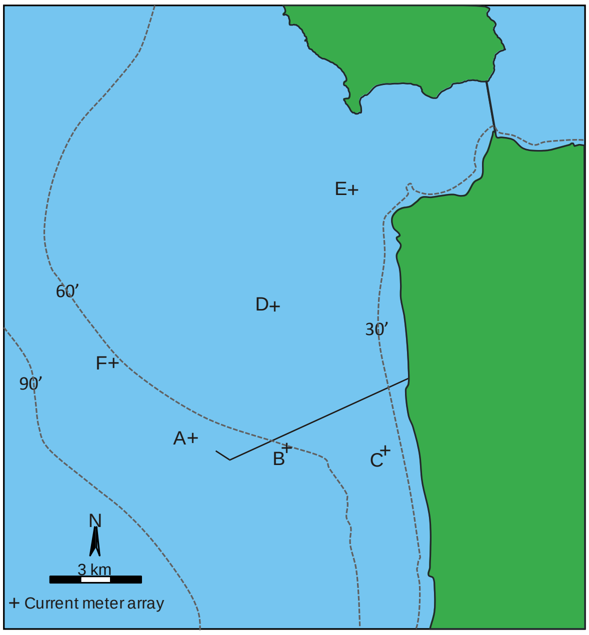

Figure 4. San Francisco Southwest Ocean Outfall

In a previous NPDES permit application, a dilution value of 76:1 was used. It was based on worst-case conditions: Highest flow rate, strongest density stratification, and zero current speed. This was considered to be an overly conservative measure of the environmental impact of the discharge, so more realistic simulations were run for the permit renewal that are described in this section. For further details, see Roberts (2007).

Field data

Extensive field measurements of currents, temperature, and conductivity were collected in the vicinity of the outfall over a period of thirteen months. Electromagnetic current meters were moored at the locations shown in Figure 4. Each meter was equipped with temperature and conductivity sensors from which seawater densities were computed. The array near the diffuser (Station A) consisted of three meters on a vertical string: near the surface, at mid depth, and near the bottom. Two “critical periods” were more extensively studied, including the period of expected maximum stratification (May to June 1988). During these two periods, field dye studies to measure dilution were conducted, and current meters were deployed at all of the stations shown in Figure 4 for approximately one month.

Some major characteristics of the currents are illustrated by the near-surface measurements in Figure 5. This shows polar scatter diagrams of the currents and the directions of their first principal axes, which are the directions that maximize the kinetic energy of the currents when projected onto them. The directions of the first principal components at all moorings generally point towards the Golden Gate. A feather plot of the May A2 (mid-depth) data is shown in Figure 6. The currents are strongly tidal, and their amplitude increases closer to the Golden Gate. Peak speeds are around 30 cm/s near the diffuser, and 100 cm/s near the Golden Gate.

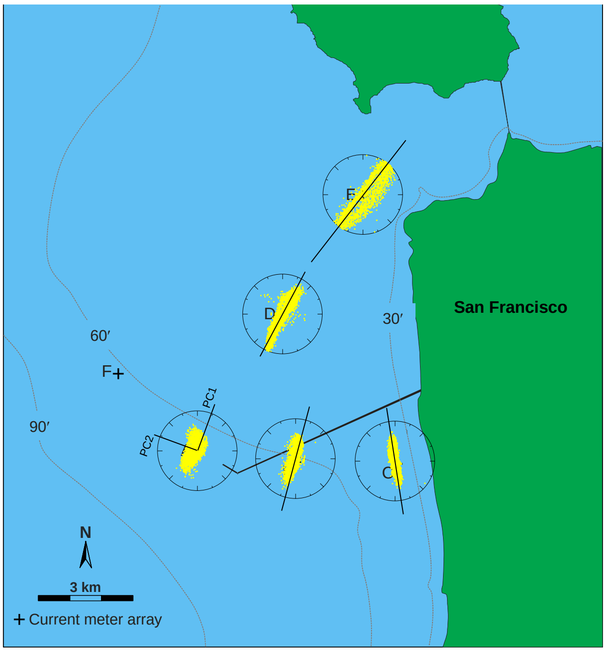

Figure 5. Polar Scatter Diagrams of Near-Surface Currents, October 1987.

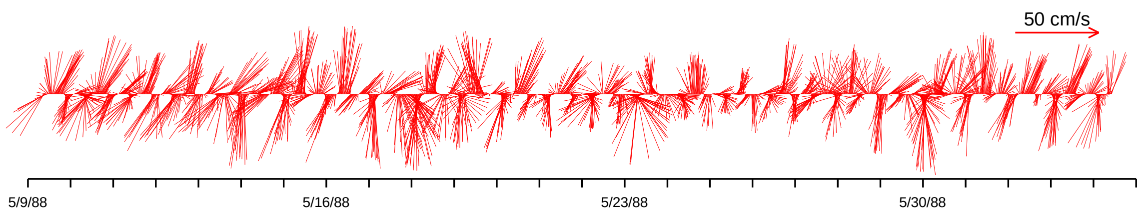

Figure 6. Feather Plot of May Currents at Mooring A2.

Seawater densities for the May data set at the three depths are shown in Figure 7. The lower plot shows the density difference between the near-surface and near-bottom instruments. This difference is of most importance here as it determines the stratification over the water column, which is crucial to plume behavior. The density is very variable, particularly near the surface, and shows clear correlations with the tide due to movement of water to and from San Francisco Bay.

Density differences over depth ranged from about 0.1 to 1.9 σ_t. Maximum stratification occurs on the ebbing tide, and minimum stratification near the end of the flood tide. The water column was occasionally homogeneous, or well-mixed.

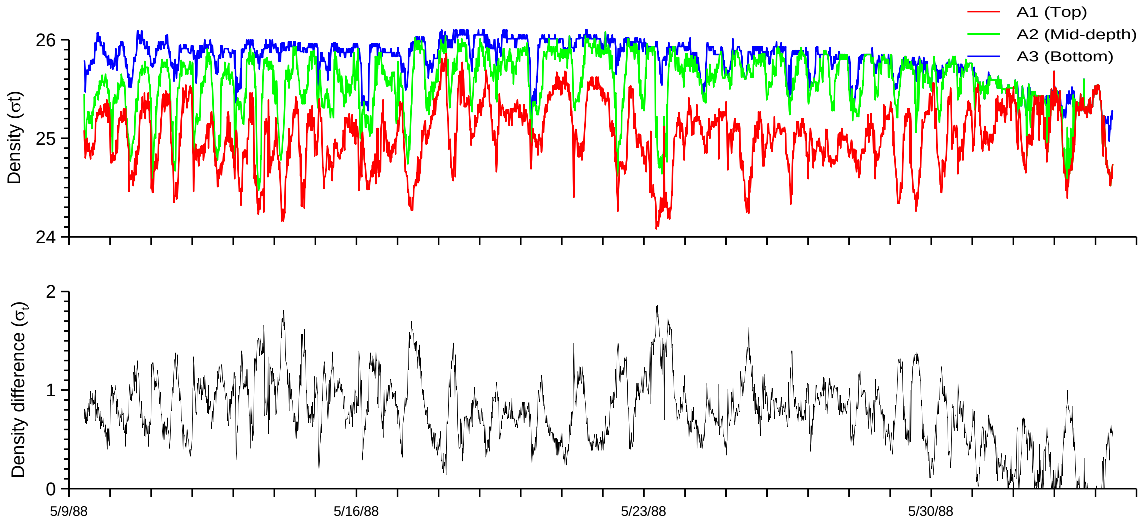

Figure 7. Density and Density Difference Between the Top and Bottom Meters, May data.

Modeling Approach

Near field dilution depends on current speed and direction, density stratification, and wastewater flow rate. All of these vary continuously and widely. Simulations of dilution were made using the mathematical model NRFIELD, described in Roberts (1999a). NRFIELD (formerly called RSB) can use long time series of oceanographic data as input. The model predicts the plume characteristics at the end of the near field. It was modified to output the dilution at a fixed distance equal to the Federal regulatory mixing zone distance of 100 m (see previous discussions). If the near field length was less than 100 m, the dilution at 100 m was assumed to be equal to the near field dilution, i.e. far field dilution due to oceanic turbulence was neglected.

The model was run with the measured currents and stratification to produce time series of predicted plume characteristics, particularly dilution and rise height. The wastewater flow was assumed to vary diurnally as shown in Figure 8. This was obtained by measurements at the treatment plant.

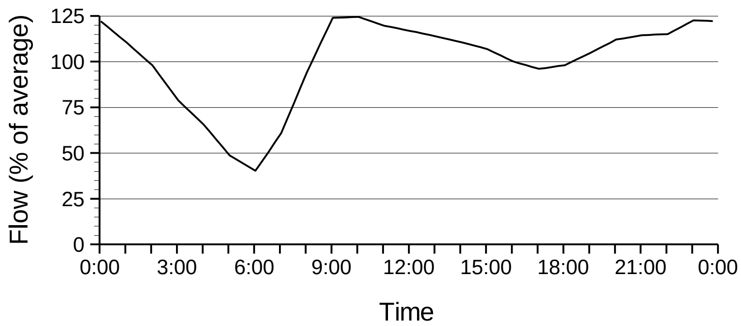

Figure 8. DW Diurnal Flow Variations Used in Simulations

Results

Figure 9 shows predicted plume characteristics for the May oceanographic data (Figure 6 and 7) and the diurnal flow rate shown in Figure 8 for an average daily dry weather flow of 0.67 m^3/s.

This figure shows time-series of dilution at the end of the near field and at 100 m, the plume rise height, and the length of the near field.

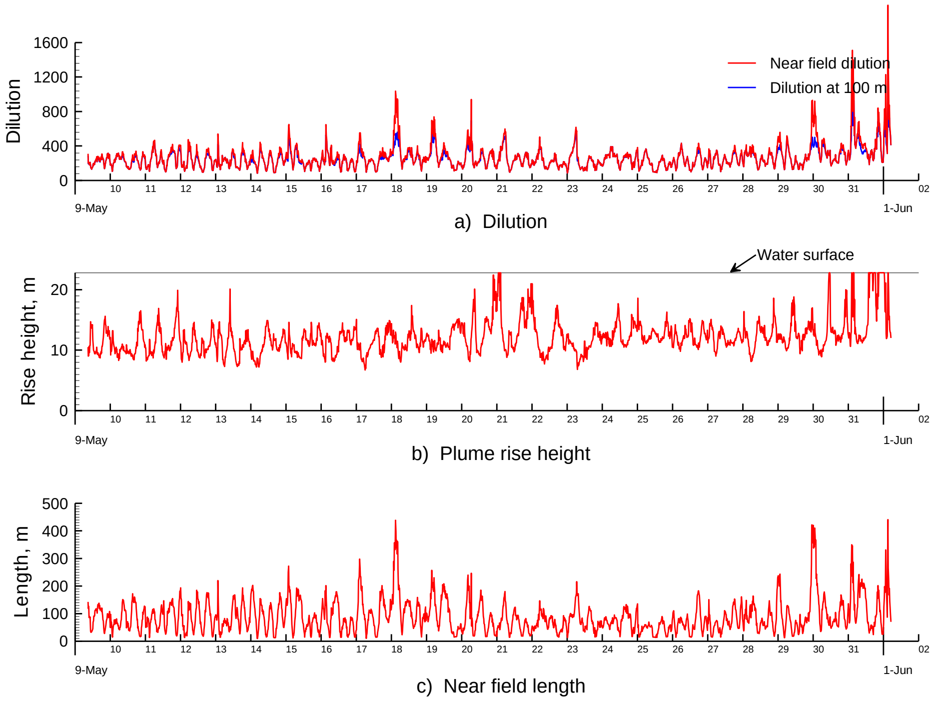

Figure 9. Typical NRFIELD Simulation Results (May Data)

Because of the widely varying flow, current speed and direction, and density stratification, the plume properties vary widely. Near field dilution varies from about 90 to 2500, with a mean value of 290. The lowest dilutions occur when high flowrate, strong stratification, and weak currents occur simultaneously. Conversely, the highest dilutions occur when low flow, high current speed, and weak stratification coincide. Low dilutions are infrequent; dilutions below 100:1 occur less than 1% of the time.

The plume is almost always submerged, with rise heights varying from 3.4 m to 22.8 m (surfacing). Overall, the plume is submerged for 94% of the time, and when the plume surfaced its dilution exceeded 210.

The length of the near field is similarly variable. It ranges from less than 10 m to about 600 m. It is less than 100 m more than 99% of the time, so the dilutions at the edge of the mixing zone at 100 m are very similar to the near field results.

The extreme dilution values have little statistical significance. Better measures are the 5 and 95 percentile values. For this case, the 5 percentile value of the near field dilution is 125, and the 95 percentile value is 582.

Lowest "worst-case" dilutions are also not a significant measure of the environmental impact of the discharge, although they have been used in permit applications. A more meaningful number is the harmonic average dilution:

$$\overline{S} = \frac{1}{\frac{1}{n}\sum_{i=1}^{n}\frac{1}{S}} \qquad (3)$$

where S is the dilution at time n. The significance of the harmonic average dilution is that it can be used to compute the time-average concentration of a contaminant after dilution as the concentration in the effluent divided by the harmonic average dilution. This average concentration cannot be directly computed from the simple mean value of dilution. The harmonic average is therefore in keeping with the spirit of the CCC (Criteria Continuous Concentration) for protection from chronic effects. The harmonic average dilution at the edge of the mixing zone for this case is 226:1.

The effects of seasonal variations on outfall dilution were also addressed by running NRFIELD with the various oceanographic conditions that were measured.

Because the currents are strongly tidal, their influence on dilution does not vary significantly through the year. The density stratification, and its effect on dilution, does vary significantly, however. Stratification depends here mostly on salinity rather than temperature. The strongest stratification occurred in winter due to increased freshwater runoff. For this period the harmonic average dilution was 169 with 100% submergence. The weakest stratification occurred in summer, when the dilution was 328, and the plume was submerged about 62% of the time.

Discussion

This example illustrates the difficulties and pitfalls in computing mixing zone properties for ocean outfall discharges and the need for clear definitions in the mixing zone regulations. Dilution is highly variable and difficult to characterize with a single number. Regulations often require "worst-case" conditions, such as strongest density stratification, peak wastewater flow rate, and no current. Use of these values results in unrealistically conservative estimates of the actual impact of the discharge, however, and may result in considerable expense devoted to unnecessary treatment. For example, the previous dilution value used for San Francisco was 76:1. But the more realistic simulations presented here show that dilutions exceed 100:1 for more than 99% of the time, and harmonic average dilutions, which are considered to be a better measure of the outfall's impact, can exceed 300:1. The difference between these numbers is large and significant. In computing the concentrations of toxic materials, for example, it could mean the difference between primary and secondary, or even tertiary, treatment with cost implications in the hundreds of millions of dollars.

The concentrations of toxics at the edges of mixing zones can be calculated from these dilutions and Eqs. 1 and 2. For the long-term (chronic) concentrations, the harmonic average dilution would be appropriate; for short-term (chronic) concentrations, probably a 10 percentile value would be appropriate. It should be noted that, for regular domestic sewage without major industrial components, outfalls resulting in initial dilutions of around 100:1 would normally meet the toxics requirements of Table 2 with preliminary or primary treatment only and more advanced treatment is unnecessary.

Even if "worst-case" conditions are specified, these should also be carefully considered. For example, the strongest stratification measured during a limited measurement campaign will not be the strongest ever expected, and has no statistical significance. It is better to use a statistical measure such as the 10 percentile stratification. Similarly, regulations might require use of zero current speed in the dilution simulations. For example the California Ocean Plan specifies "*...no currents, of sufficient strength to influence the initial dilution process, flow across the discharge structure.*" Zero currents are unrealistic in most oceanic environments, and the US EPA 301(h) regulations allow use of the 10% current speed in dilution calculations.

While we recognize the need for simplicity and consistency in environmental regulations, they should not be so stringently written as to result in unrealistically dire predictions of the environmental impact of the discharge. Statistical conditions should be employed rather than assuming simultaneous occurrence of individual worst case conditions that will in fact rarely occur together.

More advanced instrumentation is now available if specific studies and field campaigns are mandated in a permit application. In particular, Acoustic Doppler Current profilers (ADCPs) are now commonly used to measure the variation of current speed and direction through the water column. And density stratification can be measured by moored strings of thermistors and conductivity sensors. It is recommended that future measurements be made with these types of instruments to allow for improved reliability of the dilution simulations of wastefield behavior. The field program should be worked out in consultation with the regulatory authority and agreed to to ensure the appropriate data are obtained.

Another problem arises due to differing definitions of dilution. Dilution is sometimes computed as a flux-averaged value. This apparently follows from the wording in the California Ocean Plan (SWRCB, 2005), which specifies *"...the lowest average initial dilution..."* which is usually assumed to refer to a flux-averaged value. The flux average is difficult to measure in the field or laboratory, however, and the dilution values reported in such experimental studies are the minimum values (similar to centerline dilution). A more defensible and measurable definition of dilution is therefore the minimum value. Also, earlier mathematical models were conservative in not including additional mixing due to processes such as internal hydraulic jumps, and minimum dilutions predicted with newer models are often close to the flux-average dilutions predicted by older models. Predictions of differing models can also vary significantly, but regulations should not specify actual models to be used, as knowledge of mixing processes are advancing rapidly and models similarly improving.

DISCHARGE DESIGN CONSIDERATIONS

The design of an ocean outfall is a complex task that is described in Roberts et al. (2010). It should follow the following general principles: **1) The discharge location** should not be into sensitive regions. Avoid discharges where direct and immediate impacts are to be expected, such as environmentally sensitive or even environmentally protected sites, such as nearby coral reefs, lagoons, enclosed bays, within or nearby mangrove regions, and groynes. The discharge location should be in regions with good transport and flushing characteristics to avoid accumulation and allow efficient mixing. Avoid discharges in sites with stagnant flows or enclosed, protected regions, such as between structures for erosion protection or breakwaters, harbors, or very shallow waters with low current velocities. **2) The discharge structure** should avoid any direct or immediate impacts on nearby boundaries. Therefore outfalls should extend into the open water body and not directly against the bed or water surface, nor cause strong bed or surface interactions, and not be concentrated at a single point. The discharge structure should be designed to promote efficient and rapid effluent mixing. To accomplish this, alignment of the diffuser perpendicular to the prevailing currents is preferred.

These design objectives can usually be met for offshore, submerged, multiport diffusers. The offshore location provides sufficient distance from sensitive regions and the shoreline. Submerged discharges allow for adequate mixing before impacting boundaries and multiport diffusers guarantee enhanced mixing and high dilution. These objectives should be considered for several locations and design alternatives to find the optimal and most cost-effective solution.

In order to demonstrate compliance with AS for discharge consent, it appears that dischargers and water authorities must increasingly apply quantitative predictions (i.e. mathematical models) of dilution and contaminant distributions in water bodies. This holds for both existing discharges (diagnosis) as well as planned future discharges (prediction).

There are several diagnostic and predictive methods to assess the mixing from point sources and compliance with AS values:

Experiments. Field measurements or tracer tests can be used for existing discharges in order to verify whether AS-values are met and to study the fate of the substances in the receiving waters (for example, Hunt et al., 2010). Hydraulic (physical) model studies replicate the mixing process at small scale in the laboratory (for example, Roberts and Snyder, 1993). These types of studies may be costly to perform and inefficient for examining a range of possible ambient and discharge conditions and longer time periods.

Simple analytical equations or nomograms (e.g. Jirka, 2004, 2006, Roberts et al. 2010) will often suffice to predict near field plume mixing. They give rapid first estimates of the discharge conditions and are easy to handle, and so are especially useful for design discharge structures.

Mixing zone models (e.g. Jirka, 2004, 2006, Roberts et al. 2010) are simple versions of more general water quality models. They describe with good resolution the details of physical mixing processes (mass advection and diffusion), but are limited to relatively simple pollutant kinetics. This is acceptable for most applications, however, since residence times in the mixing zones are typically short so that chemical or biological mass transformations are usually unimportant.

More general multi-dimensional water quality models may be required for more complex situations. However, such calculations are time intensive and complex to apply and require expert knowledge. Such studies are typically done after preliminary designs have been developed to provide detailed environmental impact assessments.

It is important to study and analyze the water quality situation with and without the discharge, and the impact of the discharge itself. Analysis of the water quality of the water body as a whole, with the existing discharges and then the new proposed discharges, will show the changes expected and indicate the dominant pollutant sources. Such analysis allows planning further measures to reduce stresses and impacts. The analysis should simulate of the fate of the discharged substances. The siting and design of the outfall should be optimized to avoid interactions with critical regions (i.e. the shoreline). Long term effects must also be modeled carefully with and without decay and transformations (based on measurements). The results will show the impacts and the performance of the new outfall before and after discharge commences.

Statistical methods are strongly recommended for such simulations. Simulations should cover at least one year period to cover seasonal variations with detailed simulations for critical monthly periods (usually in winter and summer). For those monthly periods the exceedance frequency of substance concentrations exceeding the AS outside the mixing zone or inside specific water usage zones (e.g. beaches) is calculated usually on hourly values and compared with the allowed exceedance frequency defined in the standards. Examples of statistical modelling are Roberts (1999ab).

CONCLUSIONS

Modern water quality regulations for point source discharges often combine ambient and effluent standards. Effluent standards alone, or mandating specific levels of wastewater treatment, can result in poor choice of treatment and outfall, waste of resources, and unnecessary expense. However, the combined approach requires specification of where in the water body the ambient standards apply, for which a mixing zone regulation is needed. Some approaches and mixing zone regulations for marine discharges are reviewed in this paper. Recommendations on how to develop such regulations and define the numerical standards and mixing zone dimensions are presented. The recommendations address several concerns often stated by authorities who are reluctant to develop and apply mixing zones.

Specific examples and design recommendations are given for submerged multiport diffuser installations, so that they act as an efficient mixing device.

A case study of dilution calculations for a mixing zone permit is given for the San Francisco ocean outfall. This illustrates the difficulty of applying single numbers to highly variable oceanographic conditions and the need for careful definitions of the quantities involved.

A consequence for practical implementation of mixing zones is that water authorities must make increased use of predictive models. This includes mixing zone models for the extrapolation of measured data beyond its spatial and temporal boundaries for existing point sources and for sanctioning new sources. More general water quality models must also be used, especially for cases involving heavy pollutant loadings, multiple sources, and diffuse sources.

The dischargers themselves must be aware of the water quality response of their discharge and may apply mixing and treatment technologies to avoid concentrated pollutant plumes that travel long distances in the receiving water bodies.

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