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Review

Principles and technical application of mixing zones for wastewater discharges to freshwater and marine environments

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Abstract: A discharge mixing zone (DMZ) is a defined geographical area or volume of water in the receiving environment of a discharge where initial dilution of the effluent occurs and where exceedance of water quality criteria may be permitted. DMZs are essential to inform determination of discharge consent conditions and an important element of risk management frameworks to reduce any effects of the discharges on the environment and human health. In this review, we describe the principles and technical application of DMZs. We present an overview of the physical processes that govern the dispersion and dilution of wastewater discharges and the fate of contaminants in coastal environments and define key criteria for determining the size of DMZs. We summarize DMZ requirements in international legislation and guidance and exemplify their application to different types of discharges by means of case studies. The selected case studies illustrate different modelling tools for defining DMZs and different monitoring approaches to assess their effectiveness in achieving ecological and human health objectives.

Keywords: estuaries; zone of initial dilution; allocated impact zone; wastewater; modelling; water quality standards; water pollution control

1. Background

Globally, large volumes of wastewater generated by domestic, industrial, and commercial sources are discharged to rivers, lakes and marine waters, despite the availability of other, more sustainable, forms of use and disposal [1, 2]. In 2020, it was estimated that only 56% of all wastewater flows generated by households were collected and treated safely to at least secondary level in an appropriate facility [3, 2]. Every year, ≈730 million tonnes of wastewater and 300–400 million tonnes of liquid waste are discharged into surface waters [3]. The quality of surface waters affected by wastewater discharges continues to decline in many parts of the world, compromising the biological diversity of discharge receiving environments, the services they provide, and the role of the discharges in buffering the detrimental effects of climate change [4]. The United Nations report that only 60% of surface waterbodies assessed in 89 countries for the Sustainable Development Goal have good quality status [5]. Many of these countries have made substantial capital investments to upgrade wastewater treatment and reduce effluent disposal to rivers, lakes and coastal waters.

International best practice guidance on management of wastewater treatment and disposal identifies options to improve treatment and effluent quality, reduce the effects of the discharges on the environment and human health and, in some cases, promote re-use and recycling of treated effluents [6, 7]. When identifying locally appropriate management options, discharge consenting authorities consider many factors, such as technological and engineering constraints, the characteristics of the effluent, the hydrographical and hydrological characteristics of the receiving environment and its environmental protection designations, and community values (social, cultural, spiritual) on the potential/actual effects of the discharges.

When concentrations of contaminants in the discharge exceed those of the relevant water quality standards/limits, there is normally an area of non-compliance near the point of discharge. This occurs because it may not be technically feasible nor cost-effective to reduce contaminant concentrations in the discharge to levels below those standards/limits. Consequently, many countries have implemented discharge consenting regulations and policies containing specific requirements for discharge mixing zones (DMZs). Generically defined, a DMZ is a geographical area or volume of water in the receiving environment of a discharge where initial dilution of the effluent occurs and where exceedance of water quality standards/limits may be permitted. DMZs contribute to the sustainable management of discharge activities and help minimize their effects on the environment and human health. In practice, discharge consent authorities commonly approve a DMZ for a discharge activity where it is not practicable to avoid, re-use, or recycle the treated effluent. The consent may also specify monitoring requirements and criteria for reducing the size of the mixing zone over time.

DMZs have been applied to wastewater discharges for decades. Every discharge presents a unique set of circumstances concerning the type of effluent and the characteristics of the receiving environment. Therefore, mixing zones must be determined on a case-by-case basis. Monitoring and assessment of a DMZ should be linked to the potential environmental and human health risks and beneficial uses and values of the environment. Key gaps in the literature include the factors that influence the likelihood and the level of impact, prioritization of the issues and risks requiring management within a mixing zone, and criteria to ensure that mixing zones are kept to the smallest area possible and that there is a process to reduce it over time. Modern tools for DMZ assessments combine *in situ* observations of physicochemical parameters from moored instrument platforms, remotely operated vehicles, and testing of the wastewater contaminants of interest, high-resolution remote sensing capabilities and hydrodynamic models that provide high-resolution information to monitor the expression of discharge plumes. A challenge is how to make the best use of these tools to support more comprehensive wastewater discharge impact assessments.

In this paper, we review the principles and technical application of DMZs. We start the review by summarizing the ecological and human health effects of wastewater discharges. We outline key considerations for determining DMZs and present basic DMZ requirements in international legislation and guidance. We look in detail at statutory requirements in Canada, United States of America, Brazil, European Union and United Kingdom, and Aotearoa New Zealand. Next, we exemplify DMZ application by means of case studies. Three DMZ studies that we have undertaken were selected to illustrate different types of discharges, mixing zone requirements and water quality monitoring to determine the effects of the discharges and mixing zone boundaries. Finally, we identify gaps in knowledge and research priorities for more effective DMZ application.

Most of the DMZ information presented in this review relates to continuous discharges and therefore does not apply to wastewater spills caused by extreme weather events, infrastructure breakdown, mechanical or electrical failure, or other factors not normally considered in discharge consents. Furthermore, while the review covers various freshwater and marine environments, it is focused on coastal environments which receive the largest volumes of wastewater worldwide [4] and where the approaches to determining DMZs are more diverse.

2. Effects of wastewater discharges

2.1. Effects on the benthos and water column

Wastewater comes from a variety of sources (households, commercial and industrial facilities, hospitals, offices, etc.) and contains a variety of organic and inorganic constituents. Those of greater ecological and human health concern are suspended solids, organics that affect biochemical oxygen demand/chemical oxygen demand, nutrients, pathogens, metals, emerging organic contaminants, oil and grease, and plastics and floatables [8].

These contaminants can exert a wide range of adverse effects on discharge receiving environments and human health. For example, oxygen depletion associated with biochemical oxygen demand can be a serious problem in lakes, rivers, and estuaries. Toxic substances can cause adverse effects in aquatic organisms and humans. Many of these are synthetic chemicals such as pesticides or solvents. Some are slow to degrade while others degrade relatively rapidly [8].

The magnitude and extent of effects from these wastewater constituents is determined by many factors, primarily:

- The characteristics of the effluent (flow, volume, chemistry);
- The discharge regime (frequency, duration);
- The dispersion and dilution of the effluent after discharge;
- The physical, chemical, and biological characteristics of the receiving environment.

These effects can be detected in two main areas of the receiving environment: the bed or bottom ('benthos') and the water column. The physical, chemical, and biological characteristics of the benthos may integrate transient changes of a wastewater discharge from both dissolved contaminants in the water column and deposited organic-rich or contaminated particulate material (e.g., sewage solids). While benthic characteristics (e.g., sediment contaminants, ecological communities) can change over scales of months (e.g., seasonally) and years, they remain relatively stable over smaller timescales, and provide a good medium for detecting discharge effects [9]. However, the benthos is also sensitive to short duration, event-related change such as storm events or sewerage infrastructure breakdown [10].

In submarine outfalls (particularly those with multi-port diffusers), the enrichment of the seabed from deposition of organic particulates reduces as the freshwater effluent generally forms a buoyant surface plume which increases the initial mixing of effluent and seawater [11]. Despite this, some degree of organic enrichment can still occur and the range and magnitude of effects from wastewater and other organic-rich discharges are particularly well documented [12]. These types of enrichment effects are commonly assessed through visual observations, chemical analysis of the sediments themselves for indicators of enrichment (i.e., grain size, organic carbon, nutrients and products of microbial decomposition), and by analyzing sediment dwelling biota (including the 'infauna' living in the sediment and 'epifauna' living on it) [9, 13].

Wastewater-impacted environments often show increased concentrations of total organic carbon, total nitrogen, and phosphorus in the sediments and elevated macrophyte and benthic invertebrate biomasses [13, 14, 15]. Visual observations of epibiota and sediment characteristics, whilst cursory, provide a good general indication of the general state of enrichment [16, 17]. Often, these visual observations help to determine the need for additional monitoring such as sediment chemistry and infaunal analyses. Analysis of visual, physico-chemical, and biological indicators of enrichment may be used to assess the relative scale of effect(s). For a discharge to oceanic waters via an extended outfall, the effluent parameters of major concern are toxicants, pathogens, floatables, oil and grease, and suspended solids. For a discharge to a shallow bay or estuary, the parameters of concern include all of these as well as nutrients, color, biochemical oxygen demand, and surfactants [18, 19].

The effects of organic enrichment on the seabed usually follow a gradient of type and intensity with distance from the source, as summarized by Pearson and Rosenberg [20]. A diagram of the range of possible effects from a wastewater outfall on soft bottom habitats and the water column is provided in Figure 1. This diagram lists the type of response that macrofaunal communities can exhibit depending on the level of organic enrichment detected around the outfall. Regardless of their scale, intensity, duration or frequency, these biological effects may be influenced by other types of effects (physical, climatic, human-mediated) to produce cumulative environmental effects. These cumulative effects may be manifested by the build-up of wastewater contaminants in sediments in the area beyond the immediate area of influence of the discharge, or changes in the abundance and

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distribution of biological communities, because of the occurrence of other diffuse or point source discharges that affect the same receiving environment [21, 22]. Benthic monitoring is a reliable and cost-effective way of assessing discharge-related effects. A one-off 'snapshot' survey often provides sufficient information to determine benthic effects associated with a single discharge.

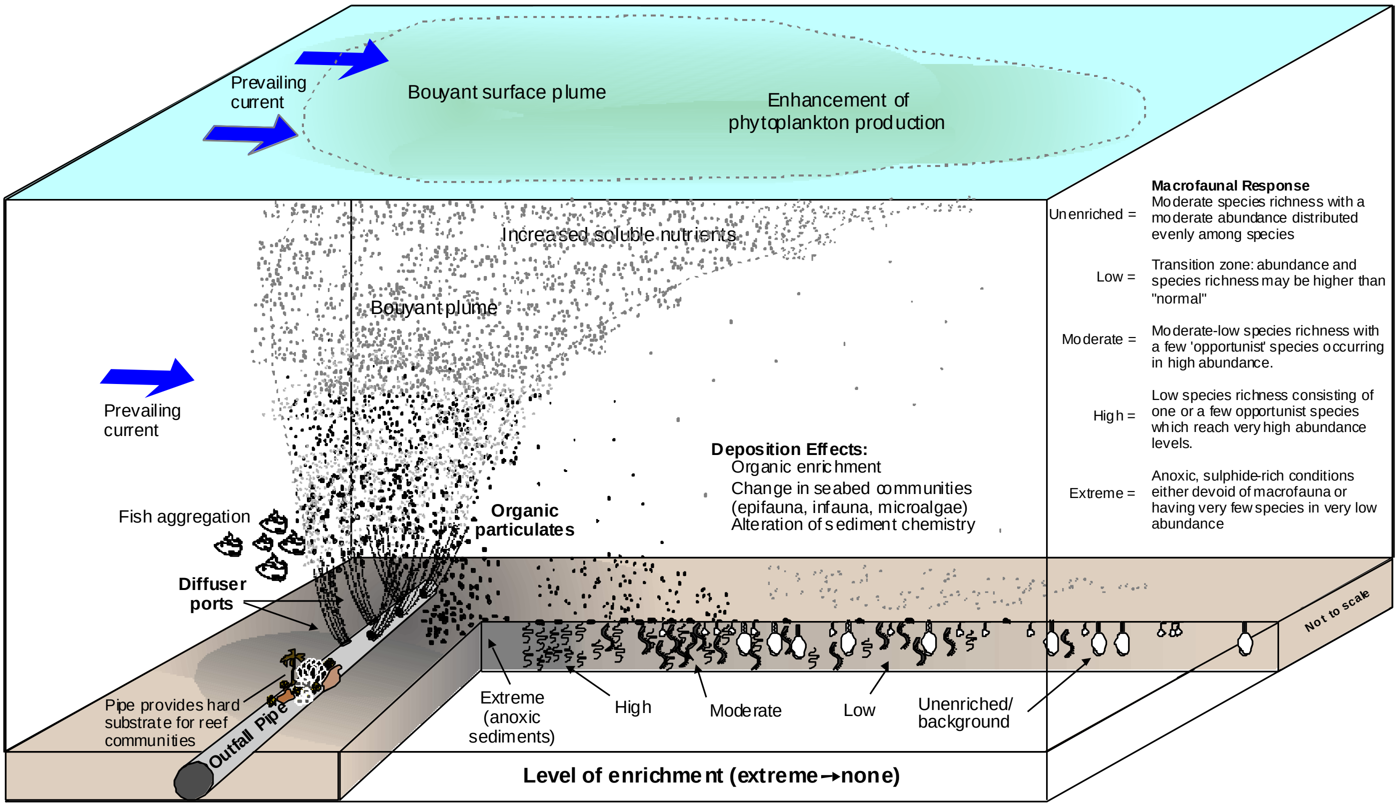

Figure 1. Schematic of potential effects of a submarine wastewater discharge on the water column and a soft bottom habitat. NB. The near field can be considered the area of highest density of organic particulates and fish aggregation near the diffuser ports. The transition zone corresponds to the area of the discharge with the lowest concentration of particulates in the upper water column (labelled as 'buoyant plume'). The boundary of the far field begins where ambient flow conditions determine plume behavior, in this case where the plume is advected to the right (areas labelled as 'Increased soluble nutrients').

The water column is a more unstable environment and background water quality changes diurnally, seasonally, and inter-annually in response to contaminant inputs and climatic events (rain events, storms, droughts). Such changes reflect both extrinsic and intrinsic processes. For example, external forces such as changing states of the tide may bring about diurnal changes in a coastal system. Because the water column is a more variable environment, multiple surveys may be required to characterize effects of discharges. Another important difference between assessing water column and bed effects is the spatial scale over which impacts may occur. While it is typical to observe a gradient of decreasing effects from the discharge point, measurable effects on water quality may extend much further than benthic effects.

Given the large number of variables associated with the water column, it is almost impossible to design a program that considers every possible set of circumstances. To overcome this, a 'worst-case' approach is often employed where effects are assessed under minimal mixing conditions, such as low-slack water and low winds [23]. Under higher currents and winds, both dilution and dispersion are increased.

In high-energy sites such as open marine environments with large flows, tides, currents, wave action, effluent disperses quickly, and the mixing zone may be relatively

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small. In contrast, in low-energy systems such as lakes and slow streams, mixing may be slower and the mixing zone will be larger [23]. Adverse effects can be mitigated by increased treatment at the plant, an enhanced discharge regime (e.g., by using a multi-port diffuser to increase initial dilution) (see multi-port diffuser illustrated in Figure 1), and discharge to a higher energy environment where the effluent can quickly disperse. However, even when some or all of these measures are adopted, there is still a possibility of adverse effects.

2.2. Effects on human health

Human exposure to untreated wastewater has been linked to viral, bacterial, and protozoan diseases (e.g., salmonellosis, shigellosis, cholera, giardiasis, amoebiasis, hepatitis A, viral enteritis, and other diarrheal diseases) and a wide range of chronic and acute health effects [24, 25]. Consequently, the potential effects of a discharge on human health are a major consideration when determining the size and shape of a DMZ. Depending on the designated uses of the discharge receiving environment, various health-based water quality guidelines / limits may be considered for determining and regulating the DMZ. These include guidelines associated with contact recreational use, production of fish, shellfish, seaweed, and other aquatic life for human consumption, etc. Discharge consents commonly include limits and monitoring requirements for fecal indicator bacteria (fecal coliforms, *Escherichia coli*, enterococci) and, less frequently, enteric pathogens (norovirus, enterovirus, adenovirus). Also of potential concern is the accumulation of toxic substances (e.g., trace metals, synthetic organic chemicals), biologically active chemicals (e.g., hormones, antibiotics, pharmaceuticals, steroids), and plastics by edible organisms [26]. Risks of human exposure to these hazards depend mainly on the type of treatment applied to the wastewater, the distance between the discharge point and the designated site, and the water use. Table 1 lists the relative health risks associated with short (shoreline) and long marine outfalls. In this regard, a long marine outfall is considered a pipeline or tunnel structure of varying length (usually from 50 m to several kilometers) that conveys wastewater for discharge some distance from the shoreline. Risk levels increase for discharges from large populations and decrease for discharges from small populations.

Table 1. Relative risk to human health associated with two types of wastewater discharges to the coastal marine environment. Modified from WHO [27].

Type of treatment	Short outfall	Long outfall
None	HIGH	MEDIUM
Preliminary	HIGH	LOW
Primary (including septic tanks)	HIGH	LOW
Secondary	HIGH	LOW
Secondary plus disinfection	LOW	VERY LOW
Tertiary	MEDIUM	VERY LOW
Tertiary plus disinfection	LOW	VERY LOW
Lagoons	HIGH	LOW

Water and contaminant fate and transport modelling studies are usually required to demonstrate that the DMZ is sufficiently far away from the designated sites and the substances released in the discharge are not likely to cause detrimental effects on water users [28, 29]. These modelling studies may consider the potential linkages between measured/estimated concentrations of wastewater contaminants at the sites, the physical, chemical, and biological transformations of the contaminants from the source to the exposure site(s), and the frequency and duration of human exposure to the contaminants [28]. As a rule, a DMZ should not overlap a designated recreational site (e.g., swimming beach, fishing site, boating area) and should not result in water quality conditions exceeding relevant guidelines for contact recreation. Concerning aquaculture operations, the

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assessment of health effects would need to consider the species farmed, the risk management practices at the site (good hygiene practices to ensure a safe separation between potentially contaminated waters and produce), and any post-harvest treatments to ensure that farmed produce meet appropriate safety and quality standards.

3. Defining a mixing zone

3.1. Effluent mixing

The dynamics of a wastewater discharge in any receiving waterbody is controlled by water depth, ambient current, effluent density, and the design of the outfall and can be described as a mixing process occurring in two main regions: the near field and the far field [30]. The near field is the region where mixing is dominated by the discharge exit conditions, such as the size and design of the outfall, the flow rate relative to that in the receiving water, and the density of the effluent. In the far field, mixing is dominated by the ambient hydrographic conditions, lateral and vertical spreading of the discharge plume and dilution through entrainment of the plume with the receiving waters. The intermediate field is the transition between the near and the far field regions. The temporal-spatial scales associated with the near field are typically in the order of minutes-tens of meters while those in the far field are in the order of hours-kilometers (Figure 2).

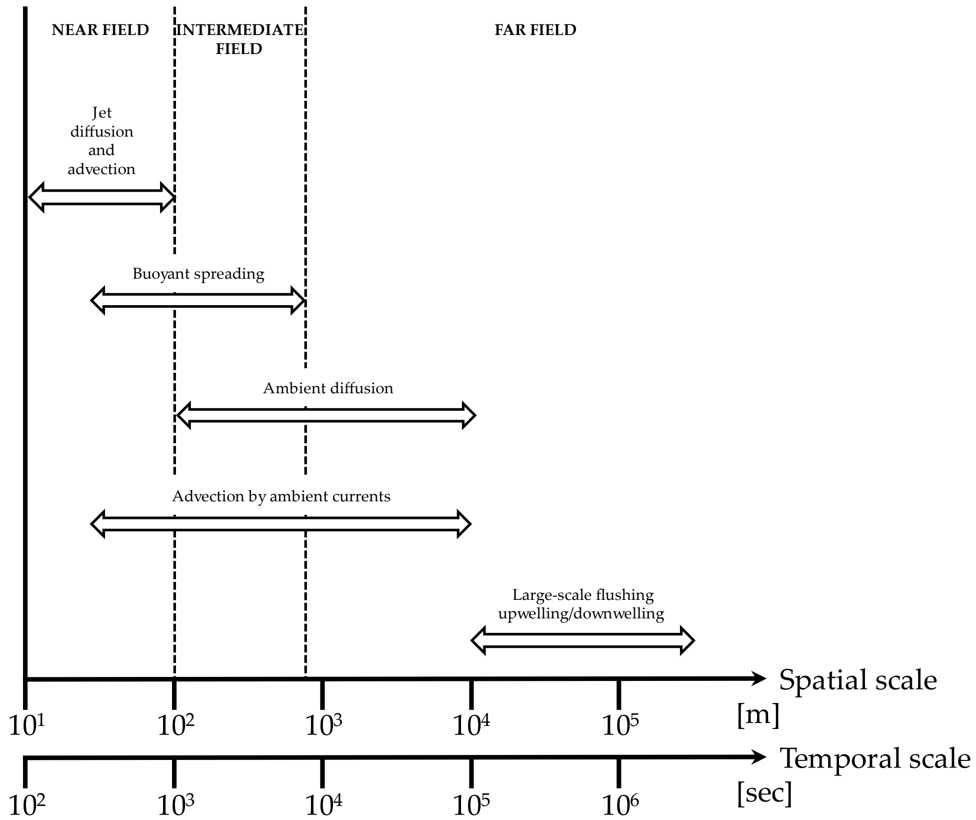

Figure 2. Reference spatial and temporal scales associated with transport and mixing processes of wastewater discharges in the marine environment. Adapted from Bleninger et al. [31].

In rivers, the rate of lateral mixing is affected by the flow rate of the receiving waters and morphology of the stream channel. The marine environment is highly energetic because of the large variations in bathymetry, and wind and tidal conditions. All these factors, together with freshwater inputs and waves, influence mixing and dilution in the water column, especially in shallower areas. Therefore, the mixing processes occurring in marine waters are more complex than those in rivers and lakes. This challenges the identification of the worst-case scenario of ecological and human health effects discussed

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above. In marine waters, the density and stratification conditions influence both the near field and the far field because they determine the vertical rise of the plume in the water column. The shear occurring between the discharge flow and the slower moving receiving waters is the main factor affecting mixing in the near field.

The physical characteristics of outfalls for discharge of wastewater to marine and freshwater environments vary widely. To increase dilution, the discharge can be subdivided into several higher speed discharges by means of a multi-port diffuser placed towards the end of the outfall pipe (Figure 1). The size and number of ports, and their orientation, also vary widely. For positively buoyant discharges, the energy of the buoyancy further contributes to accelerate the mixing and dilution of the rising plume; for negatively buoyant discharges, the initial dilution is mainly driven by the kinetic energy of the exit jet. If the diluted dense plume contacts the seabed, bottom friction delays the motion while the density difference tends to restrain mixing over the upper surface of the plume [32]. In this case, gravity plays a forcing role in plume advection, with the eventual fate of the diluted mixture controlled by seabed topography.

In the far field, where ambient conditions control plume trajectory and dilution, mixing is dominated by the background diffusion and advection by the time dependent velocity field. In discharge receiving environments with high mixing of freshwater with seawater, the resulting stable density stratification can prevent the effluent from surfacing, in which case the far field mixing is also affected by sub-surface currents [32]. It is important to note that the near field and far field regions are hydrodynamic considerations and not necessarily related to the size of a DMZ. In fact, a DMZ may include the whole continuum of near field-to-far field [30]. The study of hydrodynamic processes occurring in these regions requires the use of models and/or field dilution and dispersion studies.

3.2. Information requirements

When determining the size of a DMZ, discharge consent authorities commonly consider the following factors:

- The quality and quantity of the effluent discharged;
- The health of the receiving environment before the effluent is mixed (for new discharges, these background characteristics are best determined prior to consenting);
- The proximity of the discharge to 'sensitive' receptors, including protected habitats and other natural resources and human uses of the environment;
- The hydrodynamics of the water body (including those within the mixing zone);
- The physical, chemical and biological interactions between the discharge and the receiving environment;
- The capacity of the receiving environment to assimilate the contaminants in the discharge.

Table 1 summarizes the types of information commonly required to inform a DMZ assessment. Some types of discharge (those resulting from certain industrial activities, cooling waters, leachate, agricultural activities/confined animal operations) may require additional, more specific information not listed in the table. A conceptual model of discharge effects similar to that illustrated in Figure 1 may be developed at the outset to help identify appropriate wastewater treatment options and assessment needs for varying discharge scenarios. Many types of models have been developed to assist DMZ assessments (e.g., CORMIX, Visual Plumes) [33, 34, 35]. It is important that the selected model is appropriate to the situation in which it is being used. It is also important that the model is properly calibrated and validated to ensure that outputs are reliable and accurate. In determining discharge scenarios, seasonal factors such as increased human activity due to tourism, climatic effects on background water quality, recreational water uses, migratory species, etc. may need to be considered.

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Table 1. List of information normally used to determine a discharge mixing zone.

Type of information	Description	Useful references
Mixing zone	Description of why the mixing zone is necessary	[36, 37]
Characteristics of the effluent	Volume, flow rate and discharge frequency Temperature/density conditions Concentrations of contaminants Contaminant concentrations in the effluent relative to those in the receiving environment Evidence that discharge volume and quality have been optimized to mitigate any effects on the receiving environment Discussion of any potential contaminant bioaccumulation and/or toxicological effects on marine organisms	[23, 38, 39, 40]
Outfall/diffuser	Geographical location and design (single/multi-port diffuser, depth in relation to water surface and bed of water body) Anticipated performance (best-/worst-case scenarios)	[41]
Physical mixing of the effluent	Type of mixing zone model (water quality, particle tracking, hydrodynamic) and/or field dilution studies List of model input parameters Model calibration/validation/sensitivity testing List of data/metadata records Data suitability/limitations	[30, 42, 43, 44, 45, 46, 47]
Characteristics of the receiving environment	Type of waterbody Dilution characteristics Water temperature, salinity, dissolved oxygen conditions (ranges, seasonality) Background water quality Designated water uses and sensitive/protected habitats and resources Relevant water quality criteria/limits/standards/goals	[23, 48, 49, 50]
Assessment of ecological effects of the discharge	Nature of the receiving environment, including presence of ecologically, culturally, or economically important species Species at risk Seasonal changes in water quality or presence of migratory species Exposure of aquatic species to contaminants in the discharge	[12, 13, 14, 16, 51, 52, 53, 54]
Assessment of human health effects of the discharge	Microbiological/chemical hazards Relevant health-based guidelines/targets Recreational, fishery, aquaculture, or other uses (e.g., domestic, industrial, agricultural water supply) Risk of illness from exposure to contaminated waters	[24, 52, 54, 55, 56]

4. International regulations on mixing zones

4.1. Canada

Canada has a fragmented governance regime concerning water pollution and management of wastewater discharges to marine and freshwater environments [57]. Powers to control wastewater discharges are shared between federal and provincial governments. The large variation in regulatory and policy frameworks across provinces prompted the federal government to develop a *Canada-wide Strategy for Municipal Wastewater Management* [58]. The Strategy requires that all wastewater treatment facilities achieve minimum performance standards and develop and manage site-specific effluent discharge objectives. These effluent discharge objectives are established through site-specific environmental risk assessments that include an initial characterization of the effluent and consider the characteristics of the receiving environment and the mixing that occurs in an allocated mixing zone [58]. Medium (2,500–17,500 m^3/day) and large (>17,500 m^3/day) wastewater treatment plants (WWTPs) are required to conduct whole effluent toxicity testing. If an acute toxicity test fails due to ammonia, then the need for ammonia reduction will need to be determined based on the assimilative capacity of the receiving environment. This determination includes an evaluation of chronic toxicity, as required by the Canadian Environmental Quality Guidelines, at the edge of the specified DMZ [58].

Most wastewater discharge consents are issued by provincial environmental regulators and follow the provisions of provincial or territorial environmental protection laws [59]. In British Columbia, the key requirements are laid out in the Environmental Management Act [60]. Discharges authorized by specific regulations may have specific requirements relating to DMZs (e.g., Municipal Wastewater Regulation). In these cases, discharge applicants must comply with best management practices to reduce waste and prevent or limit harmful effects of discharge activities on the environment. Best achievable technologies for waste treatment must also be applied prior to considering a DMZ.

Discharge consenting must consider the physical mixing of the effluent to determine the area of the receiving environment influenced by the discharge. In British Columbia, the *Technical Guidance on the Development and Use of Initial Dilution Zones in Effluent Discharge Authorizations* [54] defines DMZ or Initial Dilution Zone as a "three-dimensional zone around a point of discharge where mixing of the effluent and the receiving environment water occurs" which "allows for somewhat elevated concentrations of contaminants of potential concern (COPCs) to occur within relatively small areas of a receiving water body, without significantly affecting the integrity of the water body as a whole" [54]. The Technical Guidance recommends authorization of DMZs for point source discharges to surface waters that meet the following conditions:

- Best management practices for preventing or limiting harmful impacts to the environment should be applied;
- Best available technologies have been considered in the proposed discharge activity. A DMZ should not be used as an alternative to reasonable and practical treatment of effluent or effluent stream;
- Effluent discharge and water quality within the DMZ should not be acutely toxic to aquatic life;
- Contaminants of potential concern should not bioaccumulate to levels harmful to receptors as a result of conditions within a DMZ;
- Contaminants of potential concern should not accumulate to acutely toxic levels in the water or sediments of the DMZ;
- Conditions within a DMZ should not attract aquatic life or wildlife, causing increased exposure to contaminants of potential concern;
- Negative aesthetic qualities or other nuisance conditions in the receiving waters (e.g., odor, color, scum, oil, floating debris) should not occur as a result of the discharge and/or DMZ;
- Dominance of a nuisance species should not occur as a result of conditions within the DMZ that are due to the discharge;
- Use of a DMZ should not impair the integrity of the water body as a whole.

The Guidance contains some additional requirements for reviewing proposed DMZs:

- A DMZ should be as small as possible to minimize the extent of the receiving environment potentially exposed to chronic toxicity levels;
- A DMZ should not adversely affect sensitive aquatic habitats (e.g., spawning, hatching, rearing areas for fish, overwintering habitats for fish or migratory waterfowl, areas used for aquaculture, etc.);

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- A DMZ should maintain adequate zones of passage for migrating fish that do not deter the fish from passing through, do not affect their sense of orientation, and do not pose health risks to migrating species;
- A DMZ should not result in an adverse effect at the edge of the zone on designated water uses in the area (livestock watering and irrigation, drinking water and recreation, etc.).
- A DMZ should not be sited near drinking water intakes or food harvesting areas (e.g., shellfish beds or Indigenous Peoples traditional harvesting locations);
- A DMZ should consider setbacks from sensitive areas;
- A DMZ should avoid highly frequented recreational water use areas (e.g., public beach);
- At the edge of the DMZ, water quality should not result in short-term or long-term effects to aquatic life;
- DMZs for adjacent authorized effluent discharges should not overlap with each other;
- The effluent plume within the DMZ should not contact the shoreline of a water body in any manner that would prevent effective mixing and/or result in accumulation of contaminants of potential concern in the sediments;
- Diffusers used to discharge effluent into a DMZ should be designed to maximize mixing.

4.2. United States of America

The US Environmental Protection Agency allows State Authorities and Tribes to adopt their own mixing zone regulations as part of the states' Water Quality Standards Policy 40 CFR 131.13 that apply to marine and freshwater environments [61]. In addition, the use of wastewater dilution is supported by the National Pollutant Discharge Elimination System (NPDES) permitting program 40 CFR 122.44(d)(1)(ii), which requires the discharge consenting authority to consider, where appropriate, "the dilution of the effluent in the receiving water" when determining whether a discharge causes, has the reasonable potential to cause, or contributes to an instream excursion above a criterion [62]. Depending on the state or tribal Water Quality Standards and implementation policies, a consideration of dilution could be expressed in the form of a dilution allowance or a mixing zone [62].

DMZs are individually defined and implemented through the NPDES consenting process and are used to establish appropriate water quality-based effluent limits for a specific discharger's NPDES consent. The USEPA recommends that State Authorities and authorized tribes adopt, as a minimum, a statement into their Water Quality Standards specifying whether the state or tribe intends to authorize DMZs [63]. If it does, such policy must ensure that:

- mixing zones do not impair the designated use of the waterbody as a whole;
- pollutant concentrations within the DMZ are not lethal to organisms passing through the zone (lethality is considered a function of the magnitude of a pollutant concentration and the duration an organism is exposed to that concentration);
- pollutant concentrations within the mixing zone do not cause significant human health risks considering likely pathways of exposure;
- mixing zones do not endanger critical areas such as breeding or spawning grounds, habitat for threatened or endangered species, areas with sensitive biota, shellfish beds, fisheries, drinking water intakes and sources, or recreational areas.

Due to the potential additive effects of certain pollutants that could result in the designated use of the waterbody not being protected, state and tribal mixing zone policies should specify that mixing zones do not overlap. The USEPA also recommends that consenting authorities evaluate the cumulative effects of multiple mixing zones within the same waterbody [63]. The regulatory framework defines four types of mixing zones:

- *Allocated Impact Zone*: in effect, the same as a DMZ. The term has been more commonly used since the publication of guidance to determine environmentally acceptable size

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of mixing zones around point source discharges into freshwater and marine environments [36].

- *Legal Mixing Zone*: the mixing zone in a regulatory sense, i.e., the dimensions of the mixing zone as the State authority defines them as opposed to the mixing that naturally occurs in a stream [30].
- *Toxic Dilution Zone*: a sub-zone within the DMZ that attempts to limit the exposure of aquatic flora and fauna to toxic substances [30]. Two regulatory criteria for toxic substances are recommended by the USEPA: a criterion of maximum concentration for protecting against acute or lethal effects and a criterion of continuous concentration for protecting against chronic effects [64].
- *Zone of Initial Dilution*: regularly shaped area around the discharge structure that encompasses the regions of pollutant concentrations exceeding the relevant standard(s) under design conditions [65].

State regulations that deal with streams/rivers generally limit mixing zone widths to cross-sectional areas, and allow lengths to be determined on a case-by-case basis. In relation to DMZs in lakes, estuaries and coastal waters, some States specify the surface area that is likely to be affected by the discharge. Special mixing zone definitions have been developed for the discharge of municipal wastewater into coastal waters, as regulated under Section 301(h) of the Clean Water Act [30]. In 1995, the USEPA recommended a staged approach for defining DMZs [36]:

- Determine the need for zone;
- Establish the boundaries of the waterbody;
- Analyze current and future discharge data;
- Analyze ecosystem data;
- Develop environmental mapping;
- Assign relative values;
- Determine level of protection;
- Select mixing zone procedure;
- Allocate DMZ;
- Specify quality within DMZ.

4.3. Brazil

In Brazil, Resolution CONAMA No. 430 of 13 May 2011 defines mixing zone in marine and freshwaters as an "area in the discharge receiving water, estimated based on theoretical models accepted by the competent environment agency, which extends from the discharge point, and delineated by the surface area where the mixing balance between the physical and chemical parameters, as well as the biological balance of the effluent and that of the receiving waterbody are reached, being the latter specific for each parameter" [66]. In consenting a wastewater discharge, the competent authority may require a study on the assimilative capacity of the discharge receiving environment. The study must consider, as a minimum, the difference between the water quality standards prescribed by the classification of the receiving environment and the concentrations measured from the discharge point and those beyond the mixing zone [66]. In the event of a pollution source that produces different effluents or multiple individual discharges, the limits contained in the Resolution shall apply to each effluent or to the set of effluents after mixing, at the discretion of the competent environment agency [66].

4.4. European Union and United Kingdom

At the time of writing, the United Kingdom had left the European Union, but no new mixing zone regulations and policies had been implemented in the United Kingdom. Therefore, the information provided in this section applies to both jurisdictions. Directive 2008/105/EC defines Environmental Quality Standards (EQS) for priority substances or Contaminants of Concern (CoC) listed in Annex X of Directive 2000/60/EC (Water Framework Directive; WFD) and other pollutants previously regulated under Directive

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76/464/EEC. EQS are concentration values of substances or pollutants that must not be exceeded in the receiving waterbody and consider the physical, chemical, and biological effects in the waters associated with wastewater discharges [67]. Article 4 of Directive 2008/105/EC introduces the concept of mixing zones. European Union Member States are not required to designate DMZs. However, if they wish to do so, mixing zones should not affect the compliance of the rest of the body of surface water with the relevant EQS. The extent of mixing zones should be restricted to the proximity of the discharge point and should be 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, such as authorizations and/or consents, referred to in Article 11(3)(g) of Directive 2000/60/EC and any other relevant Community law, in accordance with the application of best available techniques and Article 10 of Directive 2000/60/EC, in particular after those prior regulations are reviewed." [68]. Where a Member State has designated mixing zones, the WFD River Basin Management Plans must include a description of the methods used to define such zones and the measures taken to reduce the extent of the mixing zones.

Technical Guidelines have been produced to assist Member State authorities to establish DMZs in rivers, canals, lakes and transitional waters and to determine the size and acceptability of the zones based on a tiered approach [69] (Figure 3). While Directive 2008/105/EC sets out options, it does not define mixing zones. DMZs are defined in the Technical Guidelines as "the part of a body of surface water which is adjacent to the point of discharge and within which the concentrations of one or more contaminants of concern may exceed the relevant Environmental Quality Standard, provided that compliance of the rest of the surface water body with the EQS is not affected." [69]. The tiered approach is described below.

Tier 0 is a high-level assessment to identify the presence of discharges with the potential to cause EQS exceedance for CoC [69]. Any discharges that do not contain contaminant concentrations above EQS do not require the determination of a mixing zone because EQS would provide a sufficient level of environmental protection. In Tier 1, discharges are screened to establish the level of assessment required for those identified in Tier 0 and remove from further consideration those that can be assessed using simple tests [69]. In Tier 2, an assessment of the extent of EQS exceedance is undertaken on a case-by-case basis to determine their acceptability [69]. Tier 3 consists of a more detailed analysis of individual discharges or groups of discharges by means of computer-based modelling [69]. Tier 4 is a more detailed investigation to validate the model outputs and/or refine the modelling scenarios to better characterize the discharge impacts in relation to EQS exceedance. This may involve field studies to determine if EQS exceedance can be accepted [69].

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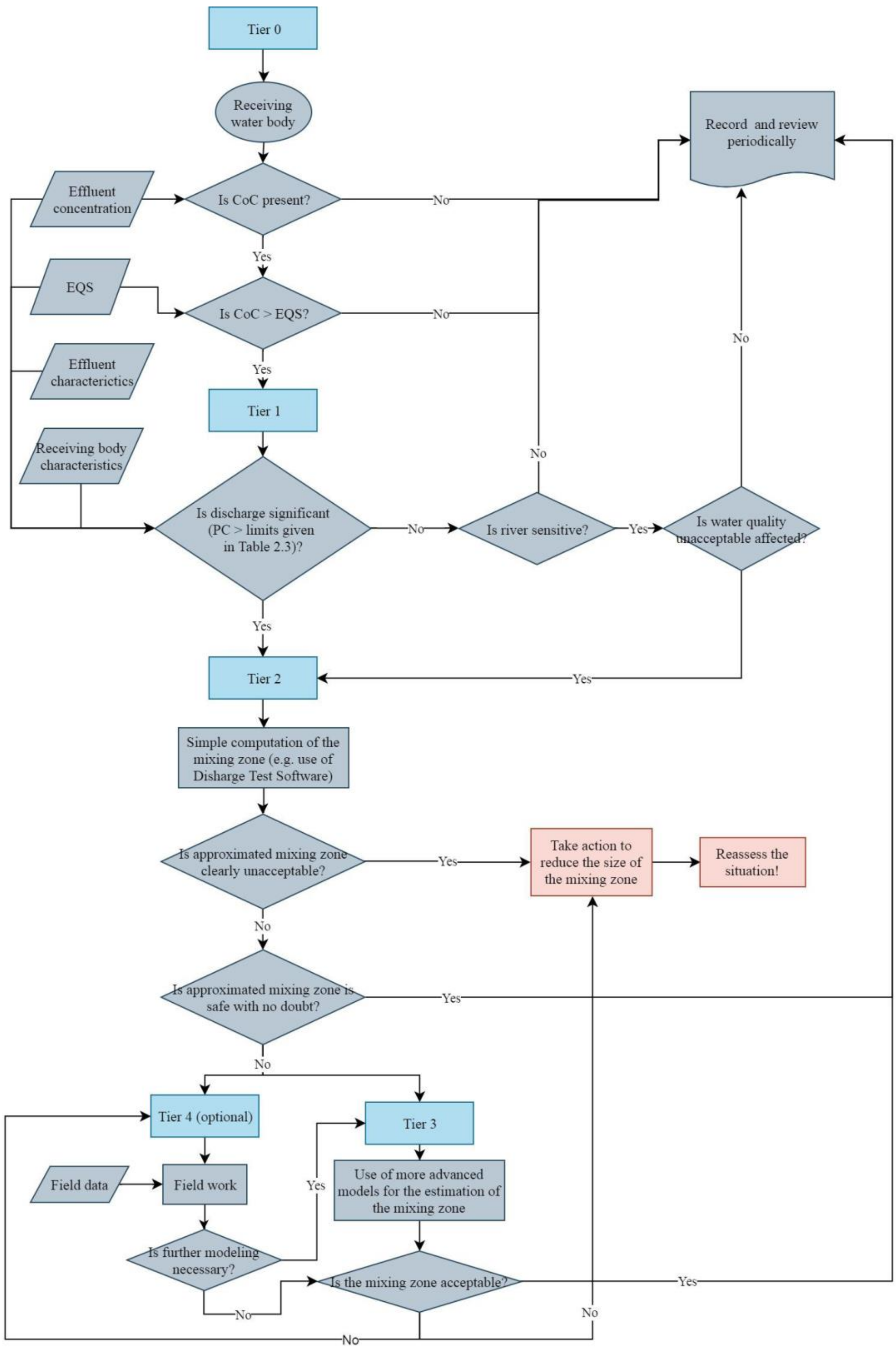

Figure 3. Tiered approach for determining the size and acceptability of discharge mixing zones recommended by the European Commission. Adapted from European Commission [69]. 'CoC' - contaminants of concern, 'EQS' - environmental quality standards, 'PC' - process contribution or the contribution of the discharge to the EQS after full mixing.

4.5. Aotearoa New Zealand

In Aotearoa New Zealand, the concept of 'reasonable mixing' is referred in Sections 69(3), 70(1), and 107(1) of the Resource Management Act (RMA) 1991 [70]. The RMA is due to be repealed by three new Acts, but the details of this new legislation have not been published at the time of writing. While the RMA is a national legislation, the control of wastewater discharges to rivers and coastal waters is a function of regional councils [70]. Under Section 70 of the RMA (Rules about discharges), any Regional Council wishing to include in a regional plan a rule that allows the discharge of a contaminant or water into water or into land in circumstances which might result in that contaminant entering water, it must ensure that, following reasonable mixing, the contaminant must not cause:

- "The production of conspicuous oil or grease films, scums or foams, or floatable or suspended materials;
- Any conspicuous change in color or visual clarity;
- Any objectionable odor;
- The rendering of freshwater unsuitable for consumption of farm animals;
- Any significant adverse effects on aquatic life."

To prevent or minimize any actual or potential adverse effects on the environment from any discharge, Councils must include a rule in a regional plan that requires the adoption of a best practicable option, taking into consideration the nature of the discharge and the receiving environment, as well as the relevant water quality standards [70].

The RMA does not define zones of reasonable mixing. The *Wastewater Monitoring Guidelines* defines these as "areas of transition within which classifications do not apply. They are effectively zones of non-compliance. From a practical viewpoint, standards can only apply after reasonable mixing of any contaminant or water with the receiving water, disregarding the effect of any natural perturbation." [19]. The Monitoring Guidelines also note that a single wastewater discharge may have one zone of reasonable mixing for seabed effects and a different zone for water column effects [19].

The NZ Coastal Policy Statement [71] also includes reference to 'reasonable mixing' and 'mixing zones'. This policy relates to "all discharges to water and provides that 'particular regard' is to be given to the sensitivity of the receiving environment, the nature of the contaminants and the capacity of the receiving environment, as well as to the mixing zone by avoiding significant adverse effects on ecosystems after reasonable mixing, using the smallest mixing zone necessary and minimizing the adverse effects on the life-supporting capacity of water within the mixing zone." The NZCPS defines 'mixing zone' as "The area within which "reasonable mixing" of contaminants from discharges occurs in receiving water and within which the relevant water quality standards do not apply" [71]. This definition is similar to that used in the Monitoring Guidelines.

Mixing zones are more commonly applied to manage discharges of soluble toxicants that do not bioaccumulate [23]. They are not applicable to certain waters where values or characteristics are not compatible with the existence of a wastewater discharge, which does not meet ambient management goals. Examples include waters with significant and regular use for primary contact recreation, aquaculture, and high conservation values [23].

In general, the size of a DMZ is not tailored to the volume and nature of the discharge, but rather the volume and nature of the discharge must fit the standards and criteria set out in a regional plan (e.g., Regional Council's Coastal Plan). If a coastal plan specifies a discharge as a consented activity, it must specify the size of the DMZ or, alternatively, define reasonable mixing to provide certainty as to the standards for a consented activity. If those standards cannot be met, consent to discharge will be required. There are various water quality guidelines referenced in regional plans which apply after reasonable mixing. Whilst there is no statutory requirement to apply reasonable mixing to these guidelines, if they are translated into standards in a plan or into consent conditions, or if they are used to assess an application, then reasonable mixing should be allowed for if referred to in the guidelines [72].

5. Case studies on the application of mixing zones to different types of discharges

5.1. Effects of municipal UV-disinfected effluent on intertidal and subtidal benthic communities

This case study reports an assessment of the marine ecological effects of a discharge of secondary treated and ultraviolet (UV) irradiated effluent from a municipal WWTP by means of dye tracing and ecological surveys. The discharge consent determines a 50 m radius mixing zone beyond which any conspicuous changes in color and clarity should be avoided, and there should be no evidence of scums, oil, and grease. The consent also sets a 50 m radius mixing zone for adverse effects on aquatic life and a 100 m mixing zone for seafood safety. The study evaluated the possibility of modifying the DMZ to 100 m for all parameters in the new consent. The intertidal substrate along this coast varies from large, smoothly weathered greywacke outcrops and boulders to fractured rock reef platforms. Mobile shingle beaches with isolated rock outcrops occur in parts of the middle and lower shore levels. The seabed consists of irregular rocky reefs extending offshore from the headlands and mobile coarse sand and gravels accumulated near to the shore.

The aim of the dye tracing study was to determine wastewater dilution under relatively calm conditions (worst-case dilution scenario), on both an ebb and flood tide. Two approaches were used: a qualitative visual tracking of batches of dye (Rhodamine WT) and a quantitative continuous release of the same type of dye which measured dye concentrations in the water column via boat-mounted fluorometry.

A survey of the marine intertidal and subtidal communities was undertaken to describe the diversity and abundance of subtidal epifauna and flora near the outfall, and to assess the effects of the wastewater discharge on the local communities. Intertidal communities were surveyed by collecting sediment core samples for infauna analyses of the low intertidal zone. The shallow subtidal communities were investigated through semi-quantitative dive surveys of the outfall area and control sites.

Results of the batch dye release showed that, under offshore winds, the plume tended to pool around the end of the outfall pipe and move generally to the east in a shore parallel direction with a lesser shoreward movement on the early flood tide. The initial movement is slightly inshore, apparently from wave action and impediment of alongshore movement by a cluster of 'awash rocks'. Inshore of these rocks, the plume moved alongshore with the tide and slightly inshore due to wave action. The plume crossed the edge of the 100 m mixing zone sixteen to eighteen minutes after release, indicating a current velocity of 9.3–10.4 cm/sec. Fifteen minutes after discharge, the dye plume made shoreline contact approximately 50 m to the east of the outfall structure amongst the inshore rocks. During the continuous dye release, ≈5,000 data points were gathered in a 600 m radius from the outfall to the east, west and offshore. The calculated dilutions during both the ebb and flood tides are represented in Figure 4. During the whole study, the minimum dilution was 100:1. Dilutions of 100:1–110:1 were noted at the edge of the mixing zone to the east and at inshore locations further east and at about 200 m from mixing zone edge. Dilutions of 110:1–220:1 were noted in areas directly west of the outfall (from 30–130 m), and in areas offshore and to the east in excess of 100 m away.

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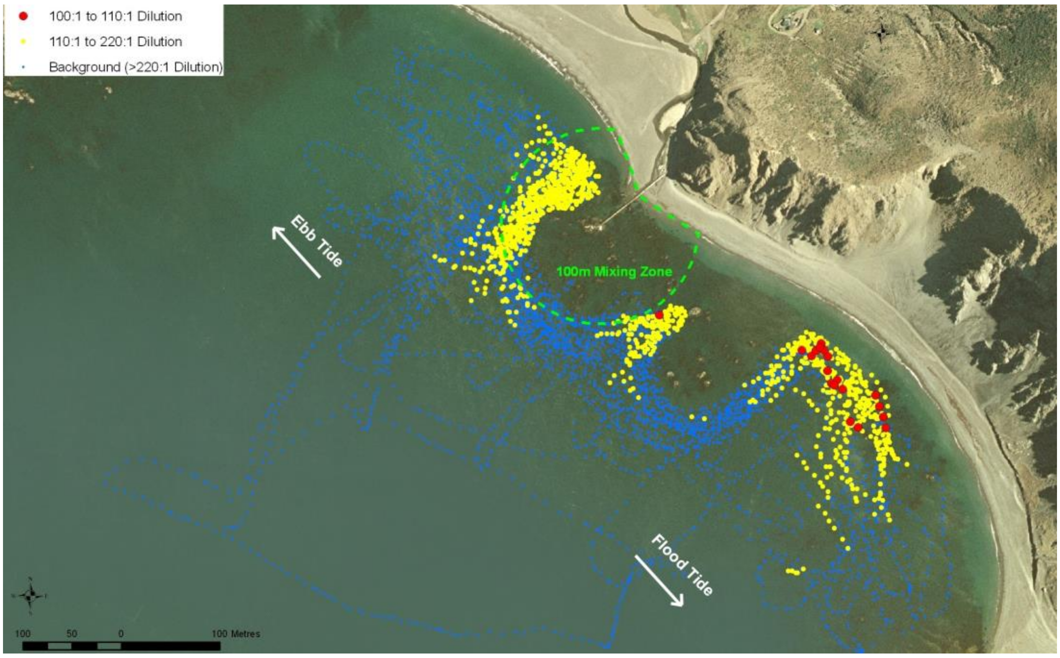

Figure 4. Calculated wastewater dilutions during ebb and flood tides.

The coarse sandy sediment contained a variety of mobile detritus-feeding amphipods and isopods; small snails; nematodes and oligochaetes typical of nutrient-rich environments; and the filter-feeding polychaete *Saccocirrus* sp. This polychaete is typical of the local interstitial spaces of coarse sandy and high energy beaches.

Non-metric multidimensional scaling (nMDS) and cluster analysis identified groups of intertidal samples based on similarities among their infaunal assemblages (three groups at a 55% level of similarity and five groups at 65%: Figure 5). The intertidal infauna community assemblage at the 50 m East site (down current from the outfall) displayed an outfall-related effect, with enhanced abundance of enrichment-tolerant taxa such as oligochaetes and nematodes. There was a pattern of enrichment extending as far as the 200 m East site and, to a lesser degree, the 50 m West site, but the 200 m West site appeared to be well beyond the influence of the outfall. The enrichment effect from the nutrient-rich wastewater did not appear to adversely affect the infaunal assemblage; rather it has enhanced and altered the abundance and richness from the more typically sparse low intertidal assemblage as observed at the 200 m West site.

The biota of subtidal reefs in 2–5 m water depths and immediately offshore from the outfall had minimal signs of outfall-related enrichment. Such communities are rarely exposed to elevated levels of nutrients due to high levels of mixing and dispersion and the effluent being largely directed back into shore by wave action upon being discharged.

The area closest to the outfall (<2 m deep), along both sides of the pipeline, and to the SE (down current) of the outfall had a lush and diverse macroalgal community consistent with an area that is mildly enriched relative to nearby control sites. In this area, the regular supply of dissolved nutrients appeared to allow many of the diverse range of algae that are common along the coastal area to proliferate. Consistent with this was an increased abundance of herbivorous fish and grazing gastropods, although increased abalone abundances were likely to be due to the absence of fishing pressure near the outfall.

The total area showing apparent signs of enrichment was 2,300 m^2 with a further 6,000 m^2 of possible enrichment. The size, shape and position of these boundaries were consistent with those identified in the dye studies. It was therefore concluded that some retention of treated effluent occurs locally, enhancing primary productivity. The result is a relatively diverse macroalgal community that enhances nutrient recycling. To this extent, the effects of nutrient enrichment were mild and were not having a significant adverse effect on aquatic life thus not precluding the establishment of the DMZ at 100 m.

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Some of the observed enrichment could be due to agricultural nutrients entering the coastal area from a stream that discharges just to the northwest of the outfall.

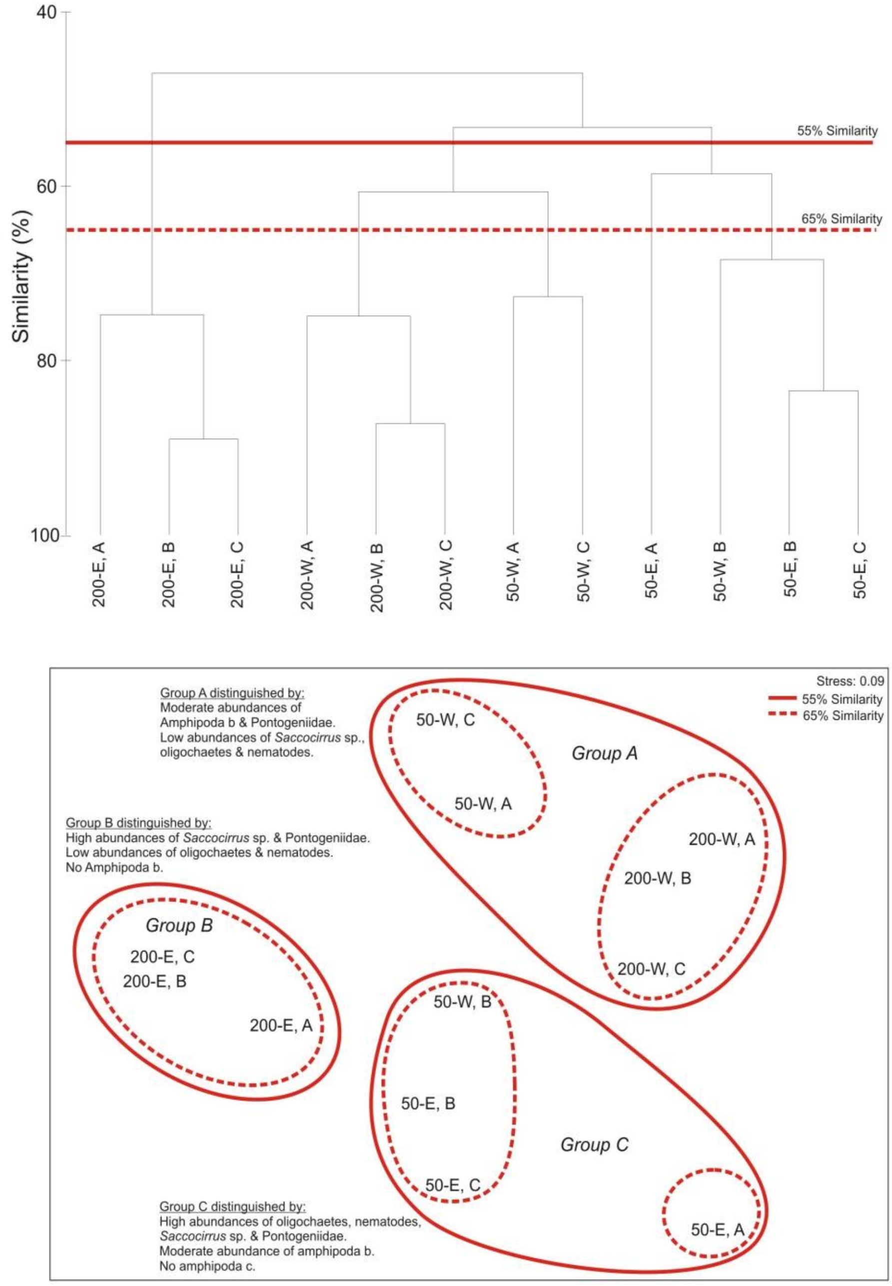

Figure 5. Cluster analysis and non-metric multi-dimensional scaling (nMDS) of intertidal infauna sampled from beach sites near the wastewater outfall. Samples linked at lower levels of similarity in the cluster analysis or closer together in the nMDS are faunally more similar. Data were 4[th] root transformed (2D stress = 0.09) and groups were formed based on 55% and 65% levels of similarity.

5.2. Effects of municipal secondary-treated effluent on recreational water quality

In this study, a mixing zone was determined for a municipal WWTP discharge of secondary-treated (oxidation pond) effluent into an open coastal area, with consideration of the extent to which the discharge complies with the relevant microbiological criteria for recreational waters (see below). From the oxidation pond system, the effluent flows under gravity through a buried pipe for approximately 350 m. The pipe terminates in a 18-m long multiport diffuser which is anchored to the seabed and aligned perpendicular to the shoreline.

The vertical and horizontal dispersion and dilution of the treated effluent were determined through drogue tracking, dye tracing, and mixing zone modelling. Drogue releases were carried out on 27 occasions over 11 months under differing tidal states (ebb, flood, slack), sea conditions, wind direction, and season to understand possible wastewater dispersion scenarios. On all occasions, the drogue was released inshore of the marker buoy at the approximate mid-point along the diffuser. Drogue positions were recorded in 10-minute intervals for the entire length of the drogue track, using a vessel-mounted GPS. The position of each drogue was tracked for about 60 minutes. Positions were post-corrected to differential GPS fixes (± 1 m) following each survey. The wind speed, direction, sea state, and tidal stage were also recorded on a logbook for the beginning and end of each drogue track.

Dye (Rhodamine WT) studies were conducted to determine both horizontal and vertical dispersion of the effluent plume, and to establish effluent mixing and dilution. The approaches for dye release were similar to those mentioned in 3.1. The dye was injected into the effluent stream at the discharge point of the oxidation pond at a constant rate using a dosing pump. The injection rate was calculated such that the concentration of dye within the effluent plume was approximately 1 g/m³ during the study. Given the discharge rate on the day of sampling (8,000 m³/day), the dye injection rate was ≈5.5 ml/min. To verify that receiving water levels could be accurately assessed, grab samples of the effluent downstream of the injection point were taken at 30-min. intervals during the study. The actual concentration of the dye in the effluent plume over time was determined by analyzing the grab samples while dye was being injected into the effluent. The dye concentration in the water column near the outfall was determined by taking vertical fluorescence profiles from a boat using a flow-through fluorometer. The plume was mapped by taking vertical profiles at discreet points along traverse transects from the long axis of the plume, recording the fluorometric value, time, GPS position and depth of the reading. These data were used to develop a contour map of dilution within the effluent plume

To compare the results of the drogue and dye studies and predict the dispersion and dilution of the effluent plume, a CORMIX2 model was developed using the effluent, diffuser and receiving water parameters summarized in Table 2. Because a close relationship between actual and predicted dilution was observed, the model was also used to predict effluent dilution at discharge scenarios up to the 15,000 m³/day peak dry weather flow.

Table 1. Summary of input parameters for the CORMIX mixing zone model.

Ambient data	
Waterbody depth	11 m
Discharge depth	11 m
Ambient current (from drogue studies)	0.18 m/s
Effluent density	1,000 kg/m³
Seafloor roughness	0.025 Manning's n
Discharge data (alternating staged diffuser)	
Total number of ports	10
Distance between ports (same side)	4 m
Port diameter	0.25 m
Distance to start of diffuser	350 m
Distance to end of diffuser	368 m
Port height off bottom	0.5 m
Effluent flow rate	9,000 m³/day
Alignment angle	97°
Receiving water density	1,025 kg/m³

Grab samples of seawater were collected on four separate occasions from six stations located along the shoreline. Stations were located 200 m and 500 m north and south of the outfall, immediately inshore of the outfall, and at the designated recreational water. Water samples were analyzed for enterococci and fecal coliforms using MPN methods.

Drogue speeds over the course of the study averaged 0.17 m/s with a maximum recorded speed of 0.48 m/s, and a minimum recorded speed of 0.03 m/s over the entire length of the track. Thus, it took the drogues from 18 min. to 60 min. to travel 250 m from the point of release at the diffuser. Drogues released on the ebb tide tended in the northeasterly direction along the shoreline while flood tide drogues ran southwesterly along the shoreline (Figure 6). The drogue releases showed that the effluent plume would move no further than 125 m inshore of the diffuser at the turn of the tide. At this point, it would be approximately 175 m from the shoreline. At 1,100 m north of the sewage outfall next to the recreational area surf break, the effluent dispersion path moved no closer than 250 m to the shoreline for all but one of the northerly drogue tracks. The most shoreward drifting drogue track passed the recreational area at approximately 175 m from the shoreline. At this point, it would be slightly offshore of the main surf break. Interestingly, the closest incursions to the recreational area occurred during relatively calm conditions. There was no evidence to suggest that an increasing swell size resulted in a more shoreward movement of the drogue path.

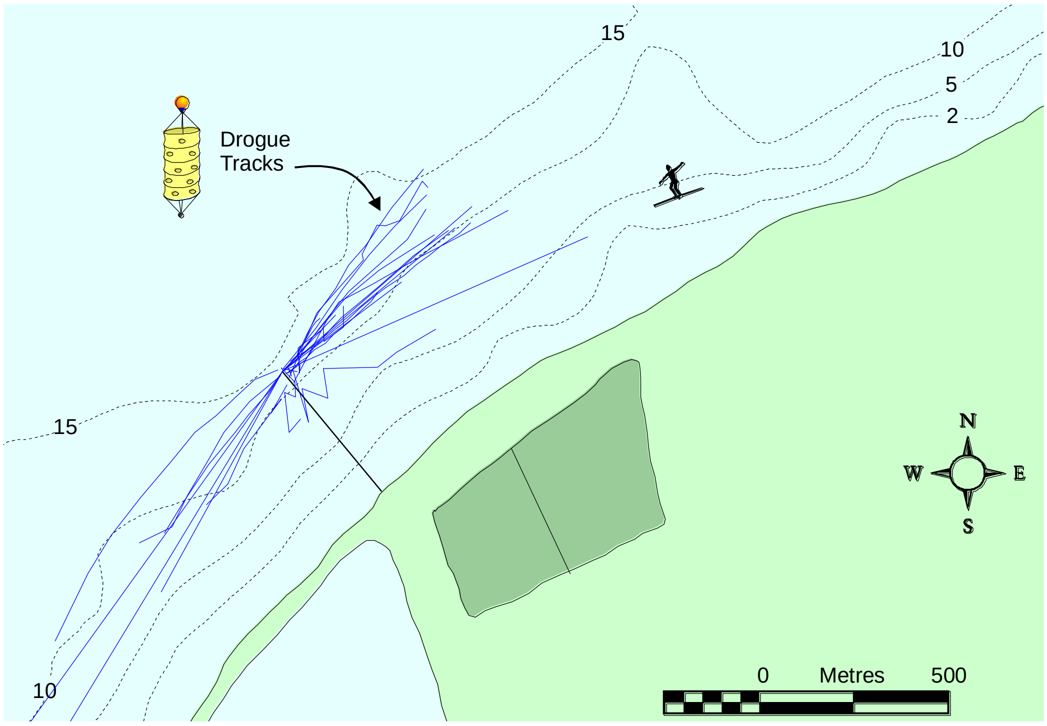

Figure 6. Summary of the drogue tracks. The recreational area surf break is represented by the black symbol ≈850 m NE of the outfall.

Visual tracking of the dye slug indicated that the plume tended to move alongshore and showed only limited lateral dispersion. The drogue that was deployed at the head of the plume stayed within the slug of dye for the entire track. Two separate continuous release dye studies conducted on a neap ebb tide (tide range 1.9 m) and on a small spring flood tide (tide range 3.7m) showed that the plume travelled parallel to the shore on both occasions. The dilution estimates derived from the dye studies presented in Figure 7 show that dilutions ≥500:1 occur within 250 m down-current of the outfall on both tides.

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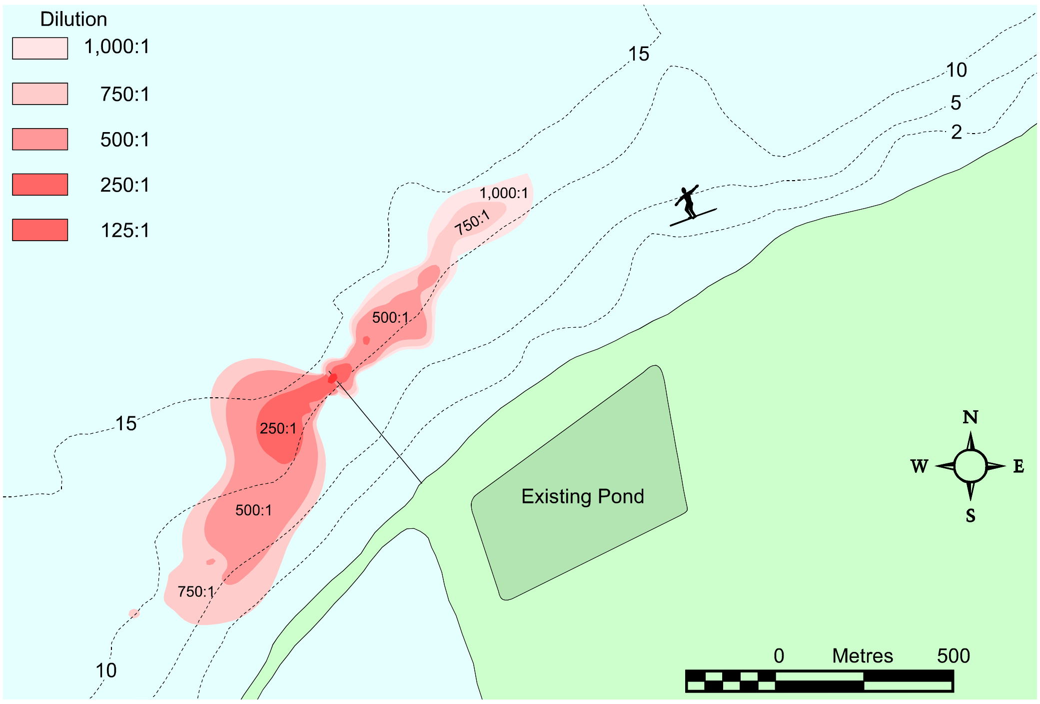

Figure 7. Summary of dye dilutions determined from the continuous releases. The recreational area surf break is represented by the black symbol ≈850 m NE of the outfall.

Concentrations of enterococci ranged from <1 to 11 CFU/100 ml and met the recreational water quality guideline (median ≤ 35/100 ml and no single sample ≥ 104/100 ml), including samples taken at 25 m from the outfall diffuser. Concentrations of fecal coliforms ranged from < 2 to 170 MPN/100 ml. The measured dilution levels show that enterococcal dilutions are slightly lower than either the CORMIX estimate and the dye tracing results indicated (Figure 8). Based on these results, a DMZ was recommended extending 250 m to the north and south of the diffuser, parallel to the shoreline, and 100 m shoreward and seaward.

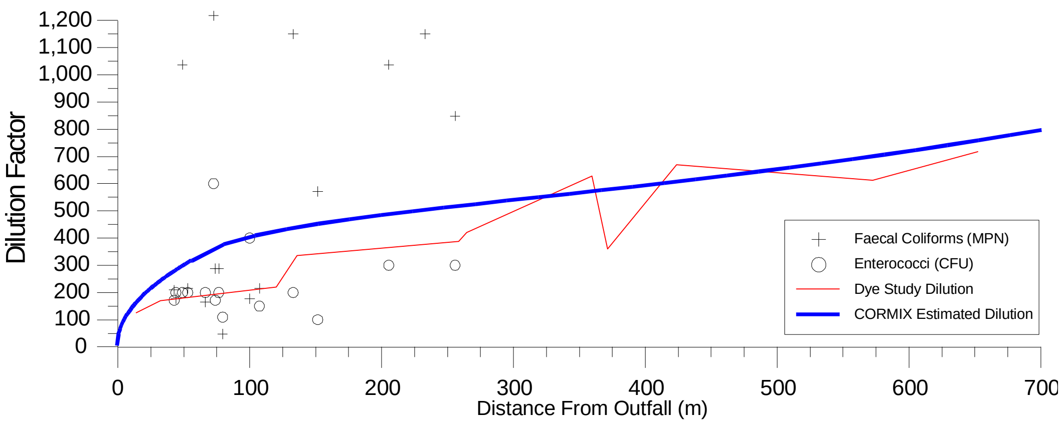

Figure 8. Wastewater dilutions estimated from dye studies and CORMIX modelling and concentrations of fecal coliforms and enterococci as a function of distance from the wastewater outfall.

5.3. Effects of an industrial discharge on physical and chemical water quality

As part of an application to renew a seabed outfall consent for a meat processing plant, the scale and intensity of coastal water quality effects of the discharge were assessed through analyses of water quality monitoring data and satellite and aerial imagery of the coastal waters adjacent to the outfall. The studies comprised a review of the available water quality data to assess the scale and intensity of contamination across the sampled area, the range and concentration of detectable contaminants at the edge of the consented 1500 m mixing zone; and delineation of the visible plume from the outfall, and relate that information to the DMZ. The water quality data included pH, salinity, color or concentrations of fecal indicator bacteria, total suspended solids, total phosphorus, total nitrogen, chlorophyll-*a* and dissolved oxygen.

Statistical analysis of the physico-chemical monitoring data did not indicate any consistent detectable effect of the discharge on surface-water quality. Minor effects on water temperature were observed within the DMZ. Temperature variation between the edge of the mixing zone was generally within 1°C of ambient at the boundaries of the DMZ, and on no sampling occasion was it more than 2°C different.

Patchy or occasional effects of the outfall were evident for three nutrient classes: dissolved reactive phosphorus (Figure 9), ammoniacal-nitrogen, and total Kjeldahl nitrogen. Nutrient peaks did not translate into detectable effects on measured biological activity (as chlorophyll-*a*). However, changes in levels of biological activity would not be expected to manifest at or near the outfall site because of the time lag between exposure to increased concentrations of nutrients and phytoplankton growth and reproduction. Bacterial contamination was high and extended beyond the 1,500 m limit of the DMZ. Concentrations of fecal coliforms and enterococci were regularly much higher down-current of the outfall. They were also higher at the down-current boundary of the mixing zone than at the up-current boundary, suggesting that the effect of the outfall on these variables extended beyond the DMZ.

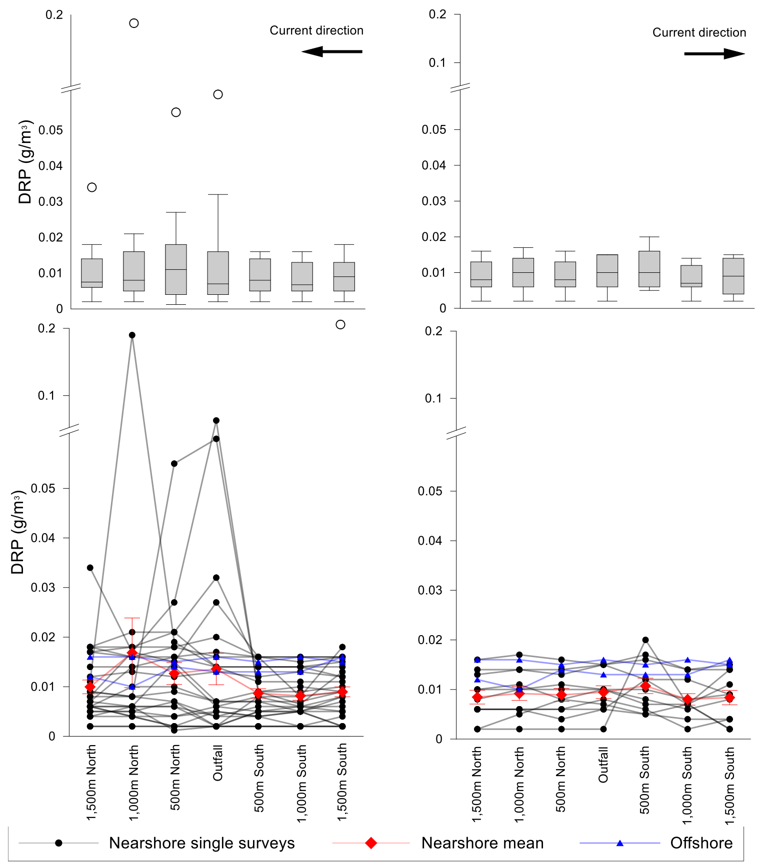

Figure 9. Seawater dissolved reactive phosphorus (DRP) concentrations within the mixing zone of the meat processing plant discharge, under north-flowing (left) and south-flowing (right) current flows. Box and whisker plots (top) indicate median values, and upper and lower quartiles (grey box). Whiskers are set with a factor value of 1.5.

NB. Current flows were northerly on both occasions when offshore samples were collected, but offshore data are presented on both line graphs for the purposes of comparison between offshore and near-shore data. Darker lines connecting symbols indicate that the same values were recorded on multiple sampling occasions.

Visual effects of the plume were frequently apparent in satellite/aerial images, and extended beyond the mixing zone on a number of occasions (Figure 10). While visual effects were not detected through the processing plant's own monitoring of Hazen color, a plume was apparent on satellite/aerial images on at least 40% of occasions for which imagery was available. The visible plume was highly variable and extended beyond the edge of the mixing zone on three of the 33 analyzable images. The images suggested that near-shore monitoring may not effectively represent optical water quality within the discharge plume.

Figure 10. Landsat 8 satellite image (captured USA time: 19-Feb-2015) showing diffuse plume extending to the south, slightly beyond the mixing zone boundary.

6. Conclusions and Recommendations

Mixing zones are an important element of risk management frameworks to reduce the effects of wastewater discharges on the environment and human health and are essential to inform determination of discharge permit conditions. Our understanding of the processes driving contaminant fate and transport has improved over time and with it the need to constantly refine approaches to the determination and assessment of DMZs. In the past DMZs were commonly set in an arbitrary way or based on best professional judgement, but current approaches are mostly based on acceptable discharge effects. This 'effects-based' approach is now expressed in many regulations worldwide. Essential topics for consideration in DMZ assessments are:

- The purpose(s) for which the effluent is managed;
- The characteristics of the discharge, including types, concentrations, and volumes of contaminants;
- The location of the outfall and timeline for improvements;
- The characteristics of the receiving environment, including the available dilution and dispersal and the proximity of the discharge to areas of ecological, recreational, cultural or economic value;
- The proposed method of wastewater treatment and timeline for improvements;

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- The need to keep the mixing zone as small as possible and to confine any 'significant' effects within the mixing zone boundaries.

In many jurisdictions such as Brazil and Aotearoa New Zealand, mixing zone regulations are vague and lack guidance on technical application. This creates many uncertainties for discharge managers, consent authorities, and members of the public. Mixing zone definitions vary widely, as evidenced by the international regulatory requirements summarized in Section 4. Consequently, their interpretation by engineers, oceanographers, biologists, and discharge consenting authorities varies considerably. The data requirements for DMZ assessments can be extensive and not easily met for some types of discharges (e.g., those to sensitive waters).

This review indicates that regulations are not always explicit about the need to apply DMZs only to circumstances where it has been demonstrated that all reasonable and practicable efforts had been made to avoid, reduce or re-cycle the effluent. Furthermore, some regulations do not include requirements for a discharge improvement plan and criteria to reduce the size of the DMZ. We consider that mixing zones should not be applied to discharges to receiving waters that already consistently fail compliance with the water quality standards (e.g., impaired waters in the USA; waters with bad ecological status in the EU) or discharges that affect sensitive, endangered, or threatened species and habitats.

Some types of contaminants (e.g., persistent organic pollutants) bio-accumulate or persist at toxic concentrations beyond DMZs. Other contaminants such as enteric viruses are shed in extremely high numbers by infected individuals and persist, potentially as infectious particles, several miles downstream from discharge points [73]. This is very problematic because it questions the level of exceedance allowed for in a DMZ, particularly where toxicity testing, persistence and bioaccumulation studies are not required by the regulations.

A DMZ assessment is a considerable undertaking, requiring collection and analysis of oceanographic and water quality data, tracer and/or modelling studies that account for varying environmental conditions, risk predictions, and engineering plans. There are many types of models available to support DMZ assessments, from simple mass balance/dilution calculation spreadsheets to complex hydrodynamic and water quality models. No single model is appropriate for all types of discharges, and a combination of models to simulate far field and near field conditions is often appropriate for ocean outfall discharges.

We recommend that discharge modelling considers, as a minimum, the best- and worst-case scenarios of effluent dilution. If 'worst-case' modelling outputs indicate consistent non-compliance with water quality standards/limits, obvious effects on the ecology of the water column and/or seabed, or a potential health effect on water users, further work involving modelling of different effluent characteristics (contaminant loading, seasonality factors, density factors) and collection of field data for model calibration and verification should be undertaken. Field studies should also be undertaken to inform DMZ assessments if the existing historical monitoring data on the receiving environment are limited.

Case studies 5.1 and 5.2 illustrate the benefits of dye tracing and drogue tracking studies to determine the time of travel and transport patterns of the effluent plume without the need to undertake complex and resource intensive hydrodynamic modelling. The main advantage of dye tracing studies is that they provide actual evidence of transport, dilution and dispersion and a more accurate determination of the overall area that may be affected by the wastewater discharge. Hydrodynamic models can reflect the effects of several discharges under a range of environmental scenarios but require large amounts of data. Case study 5.3 illustrates the value of combining *in situ* water quality monitoring with analysis of remote sensing information to determine the 'signature' of coastal discharges. Water quality information is sparse and variable in content and accuracy for most coastal areas. *In situ* monitoring is logistically difficult to collect and may be cost prohibitive for many areas. From an operational perspective, there is a strong case for investing in remote sensing capabilities to support DMZ assessments, particularly for large volume discharges. Remote sensing can provide spatially and temporally consistent information on a set of water quality variables. Through data assimilation, the information can be used to inform discharge plume modelling.

Based on the information reviewed, we suggest that further research is needed to:

- Determine the factors that determine incomplete mixing;
- Characterize the bio-transformations of persistent organic pollutants and bio-accumulative chemicals in environments receiving discharges;
- Develop a framework for cumulative effect assessments to contextualize discharge effects with those associated with other contaminant inputs;
- Determine the costs and benefits of DMZ versus alternative advanced treatment options for a range of discharges.

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