6.0 OCEAN OUTFALLS

In this chapter, the potential ecological and human health risks associated with management of treated municipal wastewater via discharge to ocean outfalls are described and evaluated.

6.1 Definition of Ocean Outfalls

Management of treated municipal wastewater using ocean outfalls involves discharging treated wastewater directly to the ocean via outfall pipes. Wastewater receives secondary treatment, including basic disinfection with chlorine.

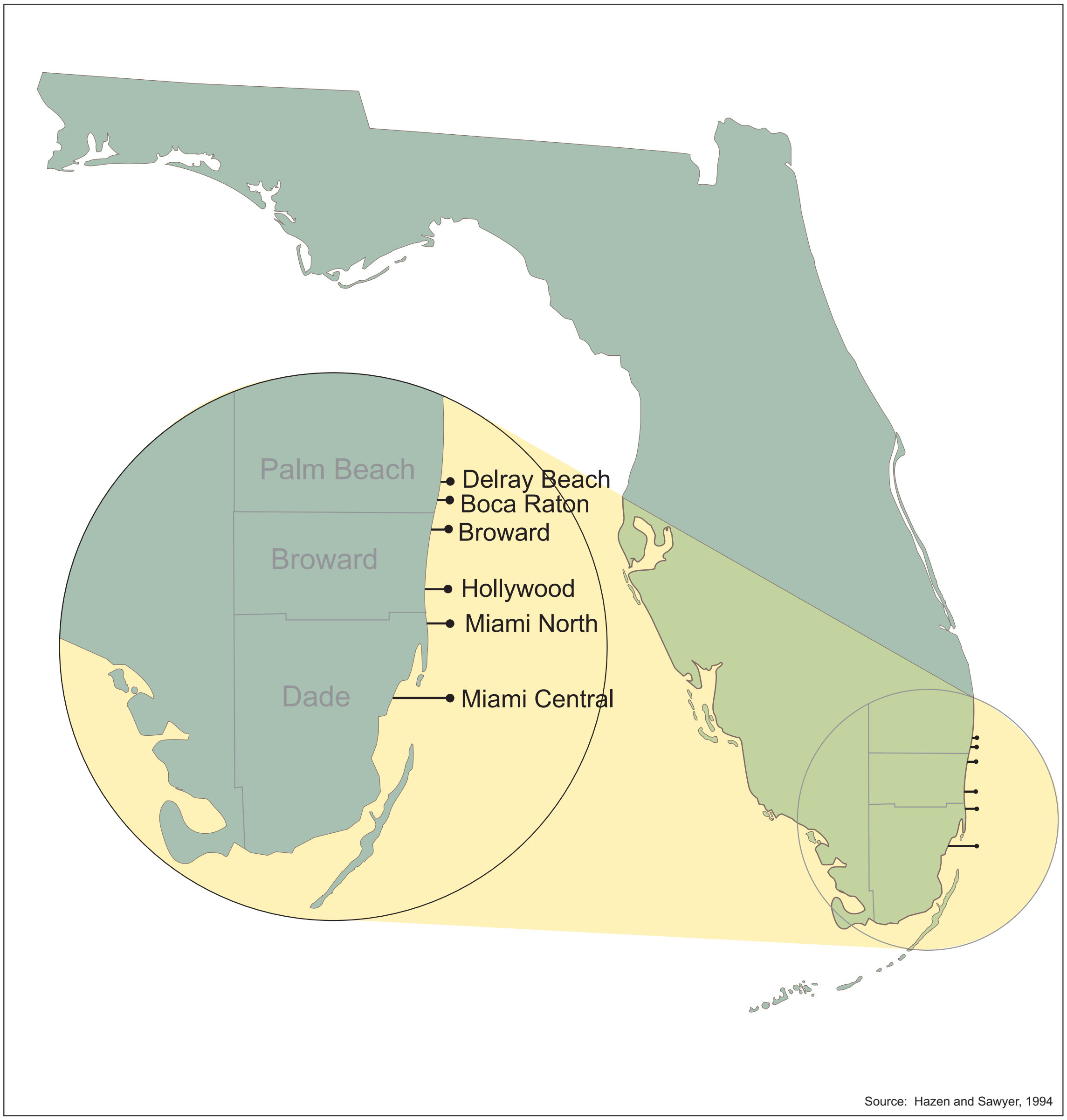
6.2 Capacity and Use in South Florida

South Florida has six publicly owned wastewater treatment facilities that discharge treated municipal wastewater to the ocean. These six facilities are the Miami-Dade Central District, Miami-Dade North District, City of Hollywood, Broward County, Boca Raton, and Delray Beach facilities (Figure 6-1). All six facilities discharge secondary-treated wastewater effluent into the western portion of the north-flowing Florida Current. Table 6-1 displays the distance from shore and the depth at which treated wastewater is discharged from these six facilities.

Table 6-1. Characteristics of Southeast Florida Ocean Outfalls

Parameter	Miami-Dade Central District	Miami-Dade North District	City of Hollywood	Broward County	Delray Beach	Boca Raton
Approximate volume discharged, million gallons per day (mgd)	133* (both Central and North)	100*	42*	66* - 80**	16.55**	13.66**
Discharge depth, meters (m)	28.2	29.0	28.5	32.5	29	27.3
Distance offshore (mi)	3.56	2.08	1.90	1.32	0.99	0.94
Number of ports	5	12	1	1	1	1
Diameter of ports (m)	1.22	0.61	1.52	1.37	0.76	0.91
Port orientation	Vertical	Horizontal	Horizontal	Horizontal	Horizontal	Up 45 degrees from horizontal

*Source: NOAA, 2002a
**Source: Marella, 1999
Source: Hazen and Sawyer, 1994.



Source: Hazen and Sawyer, 1994

Figure 6-1. Locations of Ocean Outfalls in Southern Florida

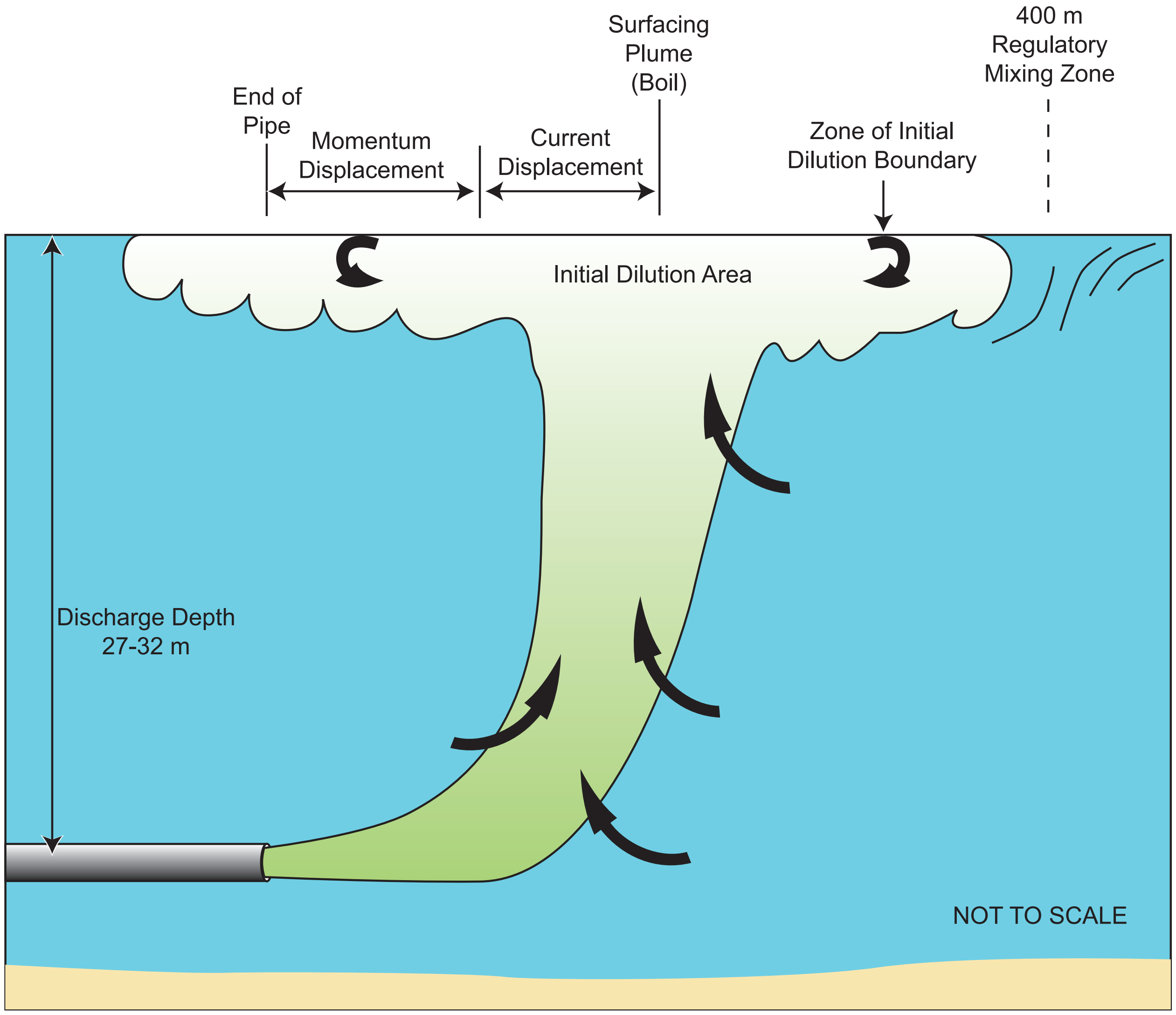
The two outfalls with the highest flow rates (Miami-Dade North and Miami-Dade Central) have multiport diffusers, while the other four outfalls with lower flow rates outfalls discharge through single ports. The Miami-Dade Central Outfall discharges beyond the 3-mile state jurisdiction into federal waters. All six treatment facilities provide secondary treatment and basic disinfection, using chlorine.

The physical behavior of effluent plumes in the ocean is well understood, based on studies at a number of ocean outfalls worldwide (Wood et al., 1993). The physical behavior of the effluent plumes from the Florida ocean outfalls has also been extensively studied. When treated wastewater is discharged into the ocean from an outfall pipe, a plume of effluent is formed that tends to rise in seawater because the effluent is less saline and more buoyant than seawater. The speed and orientation of the ocean currents are the primary factors governing plume dispersion.

Figure 6-2 illustrates the behavior of an effluent plume discharging into the Florida Current. Water column stratification; determined by water inputs, precipitation, temperature, and advection caused by winds (Wood et al., 1993), may also play a role. For example, the thermocline, (a horizontal plane at which a distinct change in water temperature occurs) may present some barrier to mixing. Off the east coast of Florida, although the plume feature may remain relatively intact near the outfall pipe, the Florida Current rapidly disperses the effluent water and constituents, diluting it and mixing it with the surrounding water.

When evaluating the potential impacts of the southeast Florida ocean outfall discharges on the marine environment, South Florida wastewater utilities and regulatory agencies recognized that additional information was needed in order to develop conditions for outfall permitting. Understanding how discharged effluent undergoes dispersion, mixing, and dilution in the ocean is particularly important for risk assessment of ocean outfalls. While earlier studies of circulation and mixing provided critical knowledge concerning the large-scale behavior of the Florida Current, they did not provide the extensive amount of detail needed to thoroughly understand and predict effluent dispersion and dilution at all six of the outfall sites.

The Southeast Florida Outfall Experiment (SEFLOE) studies were initiated in the early 1990s. The SEFLOE studies were undertaken by the wastewater treatment facilities, working closely with the Ocean Acoustics Division of the Atlantic Oceanographic and Meteorological Laboratory of the National Oceanic and Atmospheric Administration (NOAA), the Florida Department of Environmental Protection (DEP), and the U.S. Environmental Protection Agency (EPA). These studies provide a significant amount of information concerning the mixing, dispersion, and dilution of wastewater plumes originating from these six ocean outfalls, the environmental characteristics of the outfall sites, and the chemical characteristics of both treated wastewater and receiving waters. This information was used to develop recommendations for the width of mixing zones that are required under state regulations. These mixing zones are necessary to allow discharged effluent to meet water-quality standards through dispersion and dilution.



Source: Hazen and Sawyer, 1994

Figure 6-2. Effluent Plume Characteristics for Ocean Outfalls

The SEFLOE studies began with several physical oceanographic studies of effluent plume dispersion, mixing, and dilution. Effluent plumes were tracked and monitored using acoustical backscatter techniques, in one of the most extensive applications of acoustics to wastewater effluent studies in the United States (Proni, 2000; Proni and Williams, 1997; Proni et al., 1995; Williams and Proni, 1994; Proni and Dammann, 1989). Mixing zones for the southeast Florida outfall plumes were modeled using three different models that incorporated field data: CORMIX, PLUMES, and OMZA. All three models predicted realistic initial dilutions for outfalls with only minor exceptions (Huang et al., 1998). The results of these studies were used to develop wastewater treatment recommendations aimed at meeting water-quality standards within a 400-m-radius mixing zone.

Biotoxicity testing of secondary-treated wastewater and diluted effluent were conducted as well (Commons et al., 1994a). Many of these studies are summarized in the comprehensive report assembled by Hazen and Sawyer (1994). According to these studies, toxicity testing on marine organisms indicated that diluted effluent did not cause toxic effects in marine test organisms.

The initial SEFLOE I study focused on characterizing initial and farfield dilution properties of the ocean outfall plumes using acoustical backscatter techniques, determining the nutrient and bacterial content of the effluent and receiving waters, characterizing marine conditions, and evaluating concerns about nondegradable substances in the discharged treated effluent.

The SEFLOE II study continued to improve understanding of year-round physical oceanographic conditions at four of the outfalls, defining rapid dilution and mixing zones through modeling of near-field and farfield conditions. SEFLOE II also continued monitoring of nutrient concentrations in the effluent plumes. The SEFLOE II study examined the toxic characteristics of the receiving water/effluent mixture with and without chlorination, using bioassay techniques. Finally, the study examined whether the diluted wastewater met water-quality standards for priority pollutants, bacteria, and oil and grease.

6.3 Environment into Which Treated Wastewater is Discharged

Two major current systems dominate marine circulation along the western and eastern coasts of South Florida: the Loop Current, which flows out of the Gulf of Mexico in a southeasterly direction, passing the Dry Tortugas, and the Florida Current, which is the extension of the Loop Current as it flows east towards the Florida Keys and then north along the east coast of South Florida, until it joins the northward-flowing Gulf Stream (Lee et al., 1995). Smaller countercurrents, flowing west from the Florida Keys and Florida Bay, and southerly currents from the southwest Florida shelf meet the Loop Current in the area near the Dry Tortugas to form the Tortugas Gyre (Lee et al., 1995), another major eddy system. The Pourtales Gyre exists to the east of the Tortugas Gyre.

Understanding the movements of the Florida Current, particularly in its northern reaches off the east coast of Florida, is important for this risk analysis because the six ocean outfalls located in southeast Florida discharge treated wastewater effluent to the Florida Current. The Florida Current is made up in roughly equal parts of waters originating in the south Atlantic and north Atlantic subtropical gyres, connecting the Loop Current's flow out of the eastern Gulf of Mexico with the north Atlantic or Gulf Stream (Schmitz and Richardson, 1991; Lee et al., 1995). In the southern Straits of Florida, the presence of at least two gyre systems and variations in the flow of the Loop Current can cause the Florida Current to meander before it turns northward in the Santaren Channel (Lee et al., 1995).

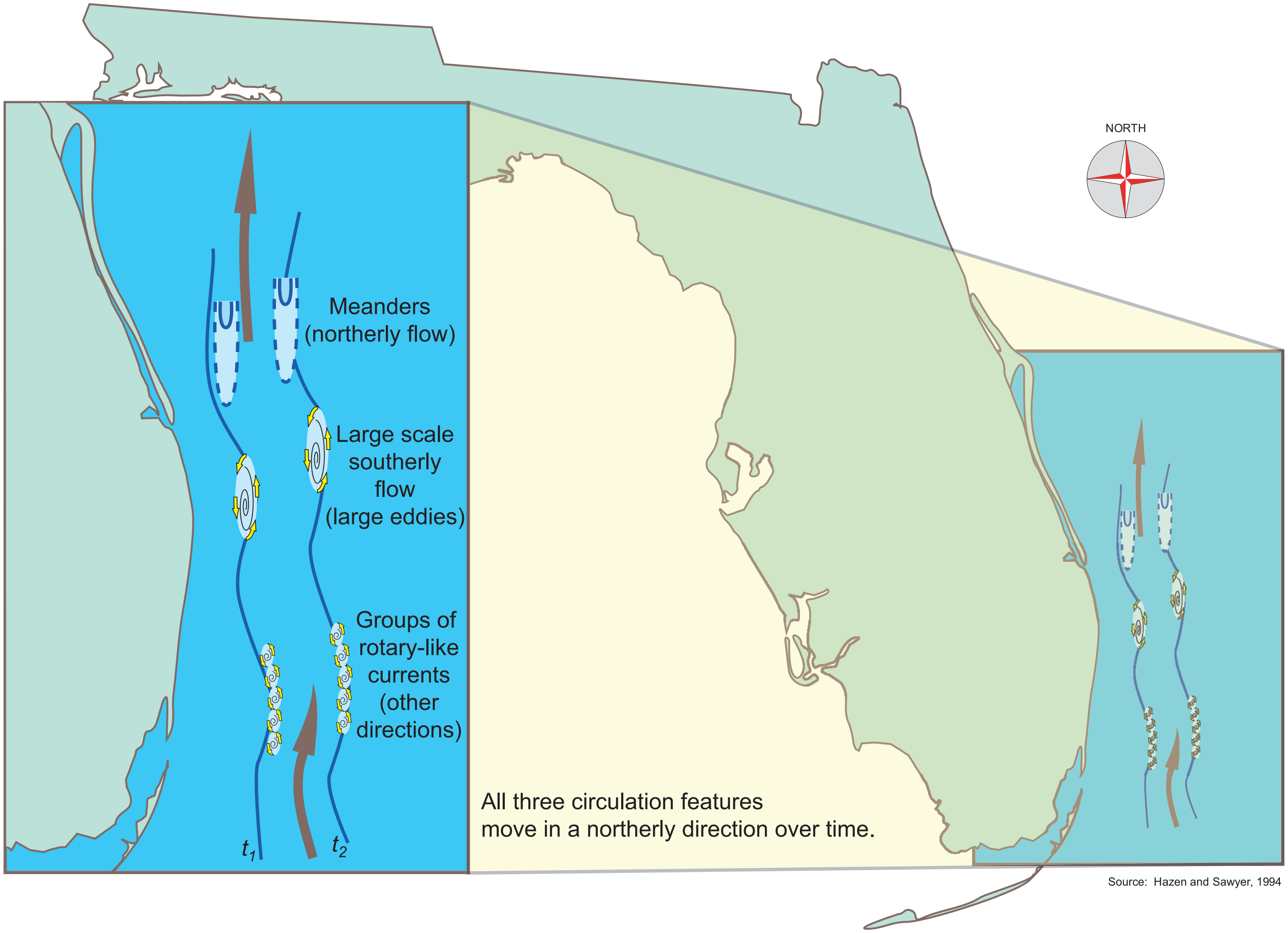
As the Florida Current travels northward off the east coast of Florida, spin-off eddies are created (Lee, 1975; Lee et al., 1995). These eddies include several components, including northerly flows associated with western meanders of the Florida Current, southerly flows, and rotary flows, composed of groups of rotations interspersed between northerly and southerly flows. Rotary flow involves water flows that move in a roughly circular manner, much as a whirlpool does. As the Florida Current moves north to join the Gulf Stream, these rotary flows also move, or are translated, in a northerly direction. These eddy and rotary flow systems were studied extensively during SEFLOE. Figure 6-3, from Hazen and Sawyer (1994), depicts the three different current regimes and their circulation characteristics, as the current moves or translates from time t_1 to a later time t_2.

The eddies and rotary flows occurring along the western boundary of the Florida Current impart a variability to the circulation system that is important for understanding potential ecological or human health risks that may be associated with ocean outfalls in this area. The variability of the Florida Current's western boundary is important because the Florida Current represents a major source of nutrients for primary productivity in the area. Incursions of the Florida Current onto the continental shelf are reflected in enhanced phytoplankton and zooplankton growth from Cape Canaveral to Cape Hatteras (Atkinson, 1985). Shorter incursions of Florida Current water onto the continental shelf, lasting days to weeks, have been recorded from Miami to Pompano (Lee, 1975; Lee and Mayer, 1977).

6.4 Regulations and Requirements Concerning Ocean Outfalls

6.4.1 General Requirements

Ocean outfalls in South Florida are required to provide secondary treatment of municipal wastewater and disinfection with the minimal amount of chlorine necessary to achieve water-quality standards. Overchlorination of wastewater containing organic materials can result in creation of organochlorine compounds such as trihalomethanes, which are associated with human health risks.



Source: Hazen and Sawyer, 1994

Figure 6-3. Circulation Characteristics of the Western Boundary Region of the Florida Current.

The federal Clean Water Act (33 USC 1251 et seq.) prohibits discharge of any waste to any waters of a state unless the waste is first treated to protect the beneficial uses of such water (see also Florida Administrative Code (FAC) 62-650). At a minimum, sewage treatment plants discharging to the ocean or other surface waters must provide secondary treatment in order to meet this pollution reduction standard.

The Florida Air and Water Pollution Control Act (Title 19, Chapter 403, Part I, Florida Statutes) also prohibits discharge of any untreated wastes to any waters of the state (FAC 62-650). In the state of Florida, waters used for recreation, propagation, and maintenance of a healthy, well-balanced population of fish and wildlife are classified as Class III Waters (FAC 62-302.400(1)). In such waters, state regulations require that, prior to discharge and after disinfection, wastewater effluent meet the most stringent of the following two standards: either (1) effluent must not exceed 20 milligrams per liter (mg/L) $CBOD_5$ and 20 mg/L of total suspended solids (TSS), or (2) 90% of $CBOD_5$ and TSS must be removed from the wastewater influent (FAC 62-600.420(1)(a) and 62-600.420(b)(1)). All wastewater treatment facilities, whether new or existing, must achieve at a minimum the specified effluent limitations (20 mg/L) and must also maintain safe pH and disinfect (FAC 62-600.420(b)(2)). The Florida DEP has also established technology-based effluent limits (TBELs), which include requirements for secondary treatment, pH levels, and disinfection.

6.4.2 Secondary Treatment of Wastewater

Secondary treatment for the state of Florida removes biodegradable organic matter and suspended solids and includes basic disinfection. Secondary treatment plants are designed to produce effluents that contain no more than 30 mg/L $CBOD_5$ and 30 mg/L TSS. The plants must also remove 85% of $CBOD_5$ and TSS from wastewater. State regulations require that, after basic disinfection, secondary-treated wastewater cannot exceed 20 mg/L of $CBOD_5$ and 20 mg/L of TSS or that 90% of $CBOD_5$ and TSS must be removed from the wastewater influent, whichever is more stringent (FAC 62-600.420(1)(a)). The effluent pH, after disinfection, must be within the range of 6.0 to 8.5 (FAC 62-600.420).

6.4.3 Basic Disinfection

Basic disinfection of wastewater must result in effluent with not more than 200 fecal coliforms per 100 milliliters (mL), at a minimum (FAC 62-600.445, 62-600.520(2), 62-600.420). When chlorine is used as the disinfection agent, the facility must provide for rapid and uniform mixing, with a total chlorine residual of at least 0.5 mg/L after at least 15 minutes contact time at the peak hourly flow (FAC 62-600.440(4)). In addition, wastewater must be disinfected so as to achieve Class III microbiological standards at the edge of the mixing zone or the level of disinfection deemed appropriate (FAC 62-600.520(2) and (3)). If the discharge is to Class III coastal waters, the disinfected effluent cannot contain more than 20 mg/L $CBOD_5$ and 20 mg/L TSS, or 90% of these pollutants must be removed from the wastewater, whichever is more stringent. In addition to these standards, bioassay toxicity tests must be conducted to ensure that aquatic organisms do not experience toxic effects from the effluent.

6.4.4 Water Quality Standards for Receiving Waters

Section 403(c) of the Clean Water Act, Ocean Discharge Criteria, applies to point-source discharges to ocean waters. Point-source discharges to ocean waters must not cause unreasonable degradation of the marine environment. Standards for receiving waters are generally more stringent than end-of-pipe limits, and thus there are regulations that pertain to the water quality of the discharge at the end of the pipe, within the mixing zone, and at the edge of the mixing zone. The Florida DEP has also established water-quality-based effluent limits to carry out the goals of the Florida statute. These limits are applied when additional treatment is necessary to ensure that the available assimilative capacity of a water body will be protected (FAC 62-650.)

Within the mixing zone, the EPA addresses acute toxicity by establishing criteria for the maximum concentrations (CMC). The CMC is approximately one-half of the acute concentration of the parameter of interest for the most sensitive species. A facility can meet these criteria by any one of the four following methods:

- Demonstrate that the CMC level is not exceeded at the end-of-pipe
- Provide rapid mixing with a high-velocity discharge so that the CMC is met a short distance from the outfall
- Meet the CMC within 10% of the distance to the edge of the mixing zone or 5 times the concentration of the parameter in local waters (Florida DEP)
- Demonstrate that a drifting organism is not exposed to average concentrations exceeding the CMC for a 1-hour time interval.

The federal, state, and local regulations require compliance with surface-water quality standards at the edge of the mixing zone. A mixing zone range is the distance needed for the effluent plume to become sufficiently diluted. The dilution occurs when the effluent plume mixes with ambient seawater to the point where the concentration of indicator bacteria reaches Class III water quality standards. The FAC allows a maximum mixing zone area of up to 502,655 square meters (m^2) for open-ocean outfalls (FAC 62-4.244(1)(h)). Water quality must meet Class III microbiological standards at the edge of the mixing zone, or the level of disinfection deemed appropriate, as described in Table 6-2 (see FAC 62-4.244 regarding mixing zones and see 62-600.520(2)). Although the mixing radius need not be circular in shape, the area required is equivalent to that of a 400-m-radius circle, which can be more easily visualized and incorporated into a conceptual model. The actual mixing zone will never be exactly circular.

Table 6-2. Federal and Florida Class III Water Quality Criteria and Guidance Values for Indicator Bacteria Groups

Group	Monthly Geometric Mean (colonies per 100 mL)	Percent	Maximum Single Value (colonies per 100 mL)
Fecal coliform	200	not more than 10% over 400	≤800
Total coliform	1,000	not more than 20% over 1,000	≤2,400
*Enterococcus**	35	not more than 10% over 70	≤140

*Guidance values
Source: Hazen and Sawyer, 1994.

6.5 Problem Formulation

In this section, general information concerning potential stressors, receptors, and exposure pathways is used to develop a conceptual model that depicts potential risk that may be associated with ocean outfalls. Section 6.6 presents an evaluation of actual risk.

6.5.1 Potential Stressors

Potential ecological stressors that may be present in secondary-treated wastewater include the following:

- Nutrients (nitrogen, phosphorus, iron) that could promote primary productivity and growth of harmful algal blooms
- Metals
- Volatile organic compounds
- Synthetic organic compounds (for example, organochlorine compounds such as trihalomethanes and chlorinated hydrocarbons)
- Other substances suspected of causing adverse effects on aquatic organisms (for example, endocrine-disrupting compounds)
- Substances whose ecological and biological effects are not yet well studied (for example, detergents, surfactants).

Potential human health stressors include the following:

- Pathogenic enteric microorganisms (bacteria, viruses, and protozoans) capable of surviving basic disinfection
- Metals
- Organic compounds
- Endocrine-disrupting compounds
- Nutrients such as nitrate and nitrite that can cause human health effects at higher concentrations.

Basic disinfection will deactivate most of the viruses and pathogens (see treatment requirements, above), but will not deactivate protozoans such as *Cryptosporidium* or *Giardia*, which must be filtered out.

6.5.1.1 Nutrients and Eutrophication

Nutrients act as potential stressors when they stimulate primary production that results in eutrophication. In coastal waters such as those of southeast Florida, as in large areas of the world's oceans, coastal, and estuarine waters, primary production is usually limited by nitrogen (Dugdale, 1967; Ryther and Dunstan, 1971; Codispoti, 1989; Paerl, 1997). However, phosphorus can be limiting under some conditions, particularly in coastal waters where there may be varying salinities. On geologic time scales, phosphorus is believed to limit marine productivity (Howarth, 1988; Holland, 1978; Smith, 1984; Codispoti, 1989; Ruttenberg, 1993). Some marine cyanobacteria, Sargasso Sea phytoplankton, and some Caribbean macroalgae are phosphorus-limited (LaPointe, 1997; Sellner, 1997; Cotner et al., 1997).

A recent National Academy review of the causes of eutrophication of coastal waters found that nutrient overenrichment of coastal marine waters have resulted in the following adverse effects (National Research Council, 2000):

- Increased primary productivity
- Increased oxygen demand and hypoxia
- Shifts in community structure caused by anoxia and hypoxia
- Changes in phytoplankton community structure
- Harmful algal blooms
- Degradation of seagrass and algal beds and formation of nuisance algal mats
- Coral reef destruction.

The National Research Council review concluded that, while nitrogen is important in controlling primary production in coastal waters and phosphorus is important in fresh water systems, both need to be managed to avoid one or the other becoming the limiting nutrient (National Research Council, 2000). The differences in causes of eutrophication between fresh and marine ecosystems stem from a variety of ecological and biogeochemical factors, including the relative inputs of nitrogen versus phosphorus within the ecosystem and the extent to which nitrogen fixation can alleviate nitrogen shortages. In addition, eutrophication of coastal systems is often accompanied by decreased silica availability and increased iron availability, both of which may promote the formation of harmful algal blooms (National Research Council, 2000).

There are exceptions to the general principle that nitrogen is limiting in coastal ecosystems. For instance, the Apalachicola estuarine system on the Gulf coast of Florida appears to be phosphorus-limited (Myers and Iverson, 1981). Howarth (1988) and Billen et al. (1991) postulate that this is related to the relatively high ratio of nitrogen to phosphorus inputs. However, in this case, the ratio may also reflect the relatively small amount of human disturbance in the watershed and the relatively low nutrient inputs overall. Howarth et al. (1995) suggests that there is a tendency for estuaries to become more nitrogen-limited as they become more affected by humans and as nutrient inputs increase overall. This is because productivity is a function of the availability of nutrients to phytoplankton.

In nearshore tropical marine systems, phosphorus appears to be more limiting for primary production (Howarth et al., 1995), while the tropical open ocean is nitrogen-limited (Corredor et al., 1999). Nutrient limitation switches seasonally between nitrogen and phosphorus in some major estuaries such as the Chesapeake Bay (Malone et al., 1996) and in portions of the Gulf of Mexico, including the so-called "dead zone" (Rabalais et al., 1999).

There are approximately 300 species of algae known to produce "red tides," including flagellates, dinoflagellates, diatoms, silicoflagellates, prymnesiopytes, and raphidophytes. Of these 300 species, approximately 60 to 80 species are actually harmful or toxic as a result of their biotoxins, nutritional unsuitability, and ability to cause physical damage or anoxia, reduce irradiance, and so forth. (Smayda, 1997). In Florida, problematic harmful algae bloom (HAB) species include *Pfiesteria* species, *Cryptoperidiniopsoid*, *Alexandrium monilatum*, *Chattonella subsalsa*, *Dinophysis* spp., *Gambierdiscus toxicus*, *Gymnodinium pulchellum*, *Gyrodinium galatheanum*, *Gymnodinium breve*, *Karenia brevis* (said to be the most common cause of red tide on the Florida coast), *Karenia mikimotoi*, and the benthic genus *Prorocentrum* spp. The Gulf coast of Florida has been typically more affected by HABs, particularly of *Gymnodinium breve*, often during the summer and fall when seasonal changes in the wind and sea surface temperature occur (FFWCC, 2001).

Toxic symptoms of HABs can affect both humans and animals and include paralytic shellfish poisoning (PSP), diarrheic shellfish poisoning (DSP), amnesic shellfish poisoning (ASP), ciguatera fish poisoning (CFP), and neurotoxic shellfish poisoning (NSP). The effects range from discomfort to incapacitation to mortality (FFWCC, 2002a).

Environmental changes that may stimulate HABs include a variety of physical, chemical, and biological factors, such as climate change, increased pollution and nutrient inputs, habitat degradation through dredging, resource harvesting and regulation of water flows, and the failure of grazing organisms to control algal growth. The two primary algal groups that produce blooms in response to nutrient inputs are the cyanobacteria and macroalgae, as well as other species from different groups (NOAA, 2002b). Even nontoxic HABs can disrupt other organisms through biofouling, clogging of gills, or smothering of coral reefs and seagrass beds in South Florida (LaPointe, 1997).

HABs can also be caused by marine cyanobacteria, commonly called blue-green algae. Marine cyanobacterial species responsible for HABs include only a few taxa, such as *Trichodesmium*, *Richelia*, *Nodularia*, and *Aphanizomenon*. *Trichodesmium*, which is nitrogen-fixing, is found in low- and mid-latitude oceans and seas of the Atlantic, Pacific, and Indian oceans. Marine cyanobacterial blooms can occur in warm stratified areas in the ocean and in embayments and estuaries where nitrogen concentrations are often low, salinities are reduced, and where phosphorus becomes enriched through upwelling, eddies, mixing, or other sources. Phosphorus limitation appears to be more important than nitrogen limitation, since some of these species are nitrogen-fixing and inhabit nitrogen-poor waters (Sellner, 1997).

Human and animal health can be affected by ingestion of the toxins created by cyanobacteria such as *Trichodesmium*, *Nodularia* and *Aphanizomenon*, as documented by livestock, canine, and human cases (Sellner, 1997; Nehring, 1993; Edler et al., 1985). Other adverse effects of *Trichodesmium* blooms include mortality of mice, brine shrimp, and copepods; asphyxiation of fish, crabs, and bivalves; retreat of zooplankton to deeper waters free of the algae; and food-chain effects (reviewed in Sellner, 1997).

In Florida, extensive blooms of cyanobacteria, involving the cyanobacteria *Lyngbya majuscula*, a species that occurs worldwide, were documented in Tampa Bay in 1999 and from Sarasota Bay to Tampa Bay in 2000. Although this species is not toxic, it can produce large slimy brown floating mats and emit a foul odor (FFWCC, 1999). The causes of these blooms are unknown, although they are not believed to be related to sewage releases.

6.5.1.2 Pathogenic Microorganisms

Potential microbial stressors in treated wastewater include pathogenic enteric bacteria, protozoans, and viruses associated with human or animal wastes. Untreated raw sewage typically contains fecal indicator bacteria (such as fecal coliforms, total coliforms, and fecal streptococci) in concentrations ranging from several colonies to tens of millions of colonies per 100 mL (see Table 6-3). Other pathogens that are potentially present include other bacteria (*Campylobacteria jejuni*, *Legionella pneumophila*, *Salmonella typhi*, *Shigella*, or *Vibrio cholerae*), helminthes (such as hookworm, roundworm, or tapeworm), viruses (adenovirus, enteroviruses, hepatitis A, rotavirus, Norwalk agent, parvovirus, and others), and protozoa (*Cryptosporidium parvum*, *Giardia lamblia*, *Balantidium coli*, *Entamoeba histolytica*) (York et al., 2002).

Table 6-3. Typical Concentrations of Fecal Indicator Bacteria in Raw Untreated Sewage

Wastewater Source	Total Coliforms (colonies per 100 mL)	Fecal Coliforms (colonies per 100 mL)	Fecal Streptococci (colonies per 100 mL)
Raw sewage	22×10^6	8×10^6	1.6×10^6

Source: Wood et al., 1993, based on data from Geldreich, 1978, for communities in the United States.

For comparison, basic disinfection of secondary-treated wastewater must achieve the microbial standards of 200 and 2,000 colonies per 100 mL of wastewater for fecal coliforms and total coliforms, respectively, depending on the type of bacteria involved. Disinfection to these levels represents reductions of 10^4 or more.

Although secondary-treated wastewater destined for ocean outfalls is treated with chlorination, the minimal amount of chlorination needed to meet Class III water quality standards after dilution is generally used, in order to avoid the adverse effects of overchlorination. Pathogenic microorganisms that are not affected by secondary treatment or chlorination include the protozoans *Giardia* and *Cryptosporidium*, which are resistant because they form cysts that can remain dormant for periods of time and can be removed only through filtration. Filtration followed by disinfection is effective at removing viruses, while secondary treatment and chlorination is effective at removing helminthes (Rose and Carnahan, 1992).

Microbial contamination from enteric viruses, bacteria, and protozoans is a chronic problem in the Tampa Bay, Sarasota Bay, and Florida Keys coastal environments. This is probably because of high concentrations of onsite sewage disposal systems, porous sandy karst soils, and hydrologic connections between groundwater and coastal embayments and estuaries (Lipp et al., 2001; Paul et al., 1995). Survival of microorganisms in water is affected by a number of physical and biological factors, such as ultraviolet radiation and predation by grazers (Wood et al., 1993). Field measurements around the world provide a range of values of the time needed for reduction of enteric bacterial populations in seawater to 90 percent of their original concentrations (that is, t_{90}). These values for t_{90} range from 0.6 to 24 hours in daylight to 60 to 100 hours at night (reviewed in Wood et al., 1993). Enteric viruses tend to survive longer in seawater than do enteric bacteria: at 20 ºC, if the t_{90} for bacteria was 0.6 to 8 hours, the t_{90} for enteric viruses was 16 to 24 hours (Feacham et al., 1983). Fecal streptococci tend to be more persistent than fecal coliforms in seawater (Wood et al., 1993).

The initial SEFLOE experiments involved the monitoring of plumes of unchlorinated treated effluent in the ocean to determine how dilution and natural attenuation processes would affect microbial concentrations of fecal coliforms, total coliforms, and enterococci. To provide guidance on the level of chlorination needed, these data were then used to calculate what the maximum bacterial concentrations in chlorinated effluent should be to achieve a given dilution at a given distance from the outfall. Southeast Florida wastewater treatment plants routinely provide secondary treatment and chlorination of wastewater to meet these standards (Hazen and Sawyer, 1994).

Because secondary effluent discharged through ocean outfalls is not filtered to remove protozoans such as *Giardia* or *Cryptosporidium*, these protozoans may pose potential human health risks that need to be evaluated.

6.5.1.3 Priority Pollutant Metals

Metals found in wastewater may constitute potential stressors because of potential human health risks and ecological risks. Metals are normally present in trace amounts in seawater (Bruland, 1984) and in higher amounts in sediments (Holland, 1978), but their concentrations are commonly elevated in wastewater because of the many anthropogenic uses of metals. As a consequence, metals are frequently used as tracers of wastewater in the ocean (Matthai and Birch, 2000; Flegal et al., 1995; Hershelman et al., 1981; Ravizza and Bothner, 1996; Morel et al., 1975). Marine disposal of untreated sewage or sewage sludge typically results in elevated concentrations of metals (typically chromium, copper, nickel, lead, silver, zinc, and iron) and other contaminants on the seafloor (Zdanowicz et al., 1991; Zdanowicz et al., 1995). Other sources of anthropogenic and natural metals to the ocean include stormwater runoff, inputs from surface water (rivers, streams) and groundwater, and atmospheric dust (Burnett and Schaeffer, 1980; Finney and Huh, 1989; Forstner and Wittman, 1979; Huh et al., 1992; Huntzicker et al., 1975; Klein and Goldberg, 1970).

Information on metal concentrations in marine organisms from this area includes the Mussel Watch Program, which is part of NOAA’s National Status and Trends Program (NSTP). The NSTP found elevated concentrations of arsenic in oysters extending from the Florida panhandle in the eastern Gulf of Mexico, South Florida (Biscayne Bay and Miami River), and up the east coast of Florida to North Carolina. Potential sources of arsenic include both natural sources (phosphorite rocks) and anthropogenic sources (for example, anthropogenic inputs to Biscayne Bay from pesticides in agricultural runoff and phosphate mining). Oysters are a food source for humans, birds, and other organisms, thus there is a potential for secondary uptake of arsenic (Valette-Silver et al., 1999). Because oysters are typically found in nearshore environments and not in deeper shelf waters, it is probable that the arsenic found in these studies originates from more nearshore or terrestrial sources, whether anthropogenic or natural. This information indicates, however, that such bioaccumulation is common and needs to be taken into consideration when examining the potential effects of secondary effluent discharge into the ocean.

6.5.1.4 Organic Compounds

Potential organic stressors that may be present in secondary-treated wastewater include EPA priority pollutant organic compounds, including volatile organic compounds (VOCs), synthetic organic compounds (pesticides, herbicides), organochlorine compounds such as trihalomethanes, and a variety of other unregulated compounds, such as endocrine disruptors, surfactants, and organic matter.

6.5.2 Potential Receptors

Potential receptors of ocean outfall effluent constituents include any organism that may be exposed to seawater containing effluent constituents. Because seawater is not used for drinking water (unless it is treated through desalination), potential receptors mainly considered in this risk assessment are those that may be *directly* exposed to seawater containing effluent constituents. Such potential receptors in the South Florida marine environment include a wide variety of animals and plants living in or near brackish coastal waters or marine waters, including marine mammals, reptiles, fish, birds, marine invertebrates, and aquatic vegetation. Humans also use the ocean for recreation, fishing, and other activities and can be exposed by eating contaminated seafood.

6.5.2.1 Ecological Receptors

Marine mammals that may be found in the South Florida coastal and marine environment include Florida manatees, whales (right, Sei, finback, humpback, sperm), and dolphins. In coastal brackish and freshwater environments such as estuaries and rivers, river otters also occur. The U.S. Fish and Wildlife Services and NOAA list all of these marine mammals except dolphins as endangered species (FFWCC, 1997).

Reptiles known to occur in marine or brackish South Florida waters include the American crocodile (endangered), Atlantic salt marsh snake (threatened), gray salt marsh snake, Atlantic green turtle (endangered), Atlantic hawksbill turtle (endangered), Atlantic loggerhead turtle (threatened), Atlantic Ridley turtle (endangered), and the leatherback turtle (endangered) (Carmichael and Williams, 1991; FFWCC, 1997).

The South Florida shelf environment is host to a wide variety of subtropical marine invertebrates, including mollusks (clams, conchs, snails, octopi, squid), annelids (worms), arthropods (crabs, lobster, shrimp), coelenterates (corals, sea anemones, echinoderms, starfish, sea urchins), sponges, bryozoans, and many others (Alevizon, 1994; FFWCC, 1997). These marine organisms feed in a number of ways, including predation, scavenging, filter-feeding, grazing, and feeding on organic detritus. Predatory invertebrates include octopi, many snails such as conchs, starfish, and squid. Filter-feeding organisms include corals, sponges, bryozoans, and bivalves such as clams and mussels. Some filter-feeding organisms, like certain corals, have symbiotic algae that help the host animal to survive. Grazing organisms include sea urchins and mollusks. Detritus feeders and scavengers include many worms, crabs, lobsters, shrimp, and snails.

The most extensive reefs of South Florida are primarily associated with the Florida Keys, but reef-forming organisms such as corals, sponges, and bryozoans may be found along the South Florida coast. Associated with these reef-forming animals may be found coralline and encrusting algae, which require solid substrates for attachment. In the Florida Keys, coral reefs have declined from a combination of factors, not all of which may be manmade. An epidemic disease occurred in the early 1980s, affecting the longspined black sea urchins that graze on the macroalgae that compete with corals for space. The absence of urchins may account for increased growth of seaweed on the reefs. Groundwater nutrient inputs from onsite sewage disposal systems may also account for the growth of macroalgal blooms, such as *Codium isthmocladum* in southeast Florida and the Caribbean (LaPointe, 1997; NOAA 2002c).

Fish species found in Florida waters include yellowtail snapper, grouper, barracuda, stingray, parrotfish, porcupine fish, Key blenny (endangered), angelfish, butterflyfish, damselfish, goby, trumpetfish, and wrasse, among many others (FFWCC, 1997).

Birds that may be found in brackish and marine waters include the brown pelican, American oystercatcher, frigatebird, piping plover (threatened), roseate spoonbill, roseate tern (threatened), cormorant, least tern, and southeastern snowy plover (threatened). Many other birds found in more inland brackish to fresh waters include the flamingo, heron, kingfisher, little blue heron, osprey, reddish egret, snowy egret, tricolored heron, white ibis, whooping crane, bald eagle, and others (FFWCC, 1997; Williams, 1983).

6.5.2.2 Human Receptors

Potential human receptors who may be exposed to ocean outfall effluent include recreational and industrial fishermen, boaters, workers associated with ocean outfall operations or wastewater treatment and, if the exposure pathways exist, recreational swimmers.

6.5.3 Potential Exposure Pathways

For nonpotable water, the primary potential exposure pathways are related to direct exposure of humans to water containing stressors and ingestion of seafood with elevated levels of contaminants. There is also a possibility of airborne exposure if water droplets containing effluent constituents somehow are formed through turbulence or aerosolization. Potential primary human exposure pathways for waterborne stressors in discharged effluent include ingestion of stressors (followed by bioaccumulation or excretion), dermal contact with stressors, and inhalation of water vapor containing chemical or microbiological stressors. Recreational or fishing activities in or near the ocean outfall could bring humans into a situation where exposure could occur.

Potential exposure pathways for marine mammals, reptiles, and fish are similar to the above-named pathways (that is, ingestion, dermal contact, and inhalation). Predation or scavenging of other organisms feeding upon contaminated organisms or algae that contain elevated tissue concentrations of effluent constituents could also cause bioaccumulation of these constituents.

Potential exposure pathways for marine invertebrates include ingestion of particles or dissolved materials containing effluent constituents. Examples include filter-feeding or detrital-feeding organisms feeding on organic particles containing adsorbed metals or organic constituents or ingesting water containing dissolved effluent constituents. Such organisms may be feeding upon the fecal pellets of other marine organisms that may have ingested effluent constituents. Predators may feed on other organisms that have already ingested or bioaccumulated constituents such as metals or organic compounds.

Settling organic and inorganic particles in the ocean represent a significant mass transport mechanism for the cycling of particles from the surface of the ocean to the seafloor. Such settling particles can scavenge other materials in the water column by adsorption or other complexation processes (Honjo et al., 1982). Fecal pellets produced by zooplankton settle to the sea floor as organic detritus, thereby providing a conduit for the rapid removal of nutrients and other substances from the upper layers of the ocean to the deeper layers of the ocean (Pilskaln and Honjo, 1987). Much of the organic matter found on the seafloor ultimately derives from primary and secondary production in the photic zone, which is typically 10 m deep (Parsons et al., 1984).

Unlikely exposure pathways include direct exposure of shallow shelf or photic zone organisms to discharged effluent. Receptors could be exposed to stressors from the physical transport of stressors towards the coast. For example, if the Florida Current were to move nearshore or if an eddy of the Florida Current were to transport effluent constituents, then nearshore or onshore receptors could be exposed to effluent constituents.

The question of whether exposure and uptake pathways exist is crucial for risk assessment. The primary risk questions to be asked are these:

- Do these actual exposure pathways exist?
- If they do exist, is there actual uptake?
- If there is uptake, are there adverse effects upon humans or biota?

Unless seawater is used for desalination for a drinking-water source, the primary type of human risk that might occur would be related to recreational or occupational exposures to seawater and consumption of seafood.

6.5.4 Conceptual Model of Potential Risk for Ocean Outfalls

A conceptual risk model is a generic model of potential risks that may result from management of treated municipal wastewater using ocean outfalls. Such a model lists all potential exposure pathways and processes that control whether a receptor is actually exposed to a stressor or not. This conceptual model of potential risk represents the risk model to be tested using specific data. Section 6.6 describes the data and the testing of the model. It contains an evaluation of how realistic the potential risks are. A conceptual model for evaluating potential risks associated with ocean outfalls is shown in Figure 6-4.

The model components that control the fate and transport of wastewater discharged into the open ocean environment were adapted from a 1984 National Academy of Science study entitled “Disposal of Industrial and Domestic Wastes: Land and Sea Alternatives” and the Waquoit Bay National Estuarine Research Reserve Watershed risk assessment model that provides a method for identifying valued natural resources and evaluating the risk to those resources (Bowen et al., 2001).

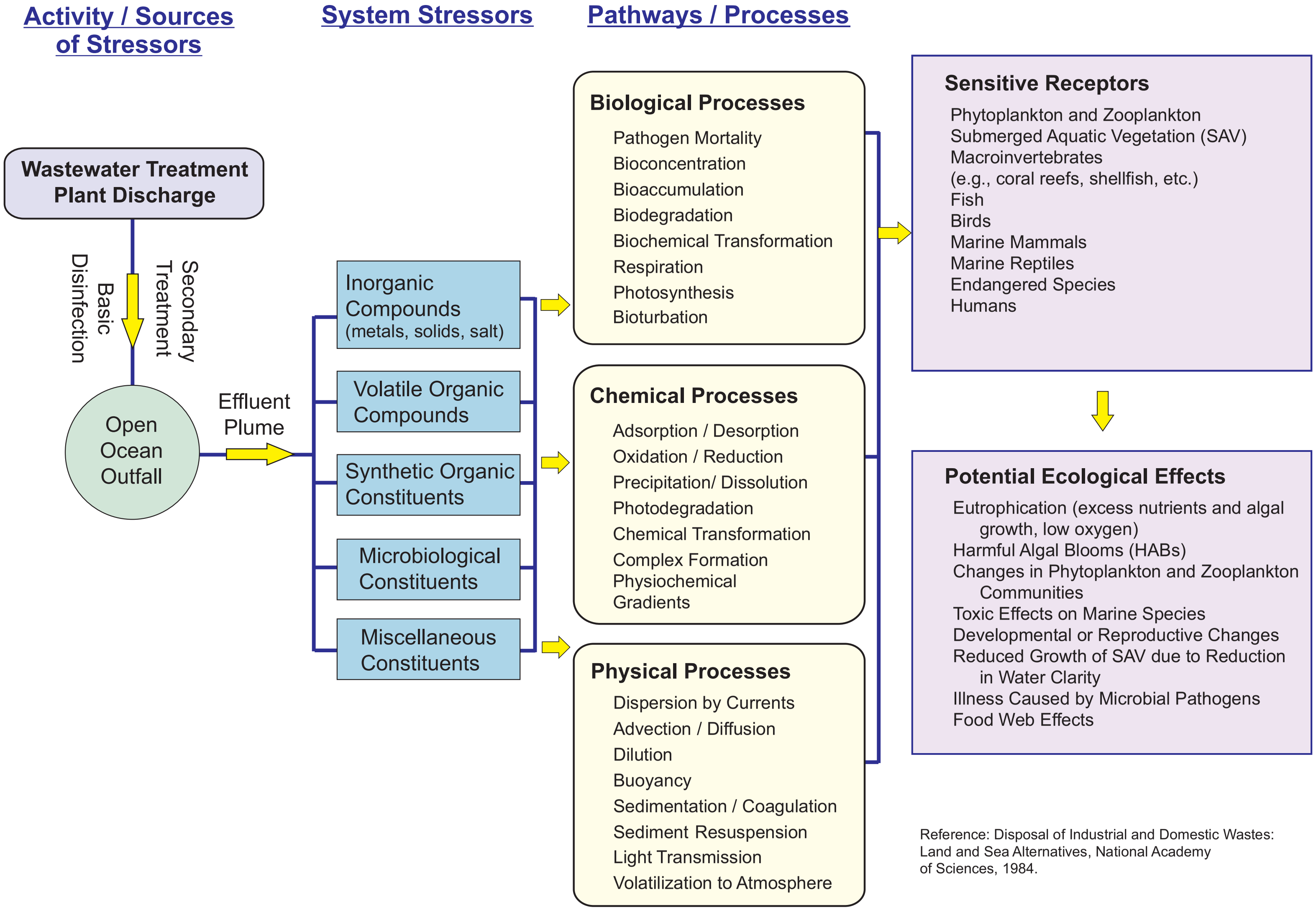
In this conceptual model, the source of stressors is the wastewater treatment plant providing secondary treatment and basic disinfection of municipal wastewater derived from industrial and domestic sources. The potential stressors are inorganic compounds (for example, metals, salts), organic compounds, nutrients, and pathogenic microorganisms.

The physical pathways and processes that occur when treated wastewater is discharged into any water body, either open ocean or surface water (such as rivers, lagoons, or estuaries), are extremely important in determining large-scale exposure pathways. In the vicinity of the outfall, the ways in which ocean currents affect dispersion and dilution of the effluent plume are extremely important. Farther away from the outfall, as dilution occurs, it is important to determine whether ocean circulation and mixing could vary enough to expose terrestrial or nearshore receptors.

Physical processes refers to the transport process that moves suspended or dissolved materials from one place to another (National Academy of Sciences, 1984). Examples include advection of a plume through current movement, dilution or dispersion of the plume through mixing with surrounding waters, density-driven advection, sedimentation of solids from the plume to the benthos, resuspension of sediment through turbulence or bioturbation, adsorption, and volatilization to the atmosphere.

Potential chemical processes are chemical reactions that wastewater constituents can undergo when discharged into the aquatic environment. These processes include adsorption and desorption, changes in oxidation state, precipitation and dissolution, photodegradation, transformation, and complex formation.

Potential biological processes affecting the fate and transport of stressors include uptake, bioconcentration and accumulation of stressors, inactivation of pathogenic microorganisms, biochemical transformation or degradation of stressors, photosynthesis, and the formation of organic marine particles such as zooplankton fecal pellets that transport stressors to benthic habitats. Both chemical and biological processes determine the fate and effect of a particular constituent.



Reference: Disposal of Industrial and Domestic Wastes: Land and Sea Alternatives, National Academy of Sciences, 1984.

Figure 6-4. Conceptual Model of Potential Risks for the Ocean Outfall Option

Potential receptors include submerged aquatic vegetation, plankton (phytoplankton, zooplankton), larger aquatic organisms (invertebrates, fish, marine mammals, and reptiles), birds, and humans. There are no drinking-water receptors in this conceptual model. If seawater were to be used for a drinking-water source through desalinization, which is being considered in South Florida, then this potential receptor would be added to the conceptual model. However, seawater in coastal areas would contain many of the same stressors derived from other sources on land.

6.6 Risk Analysis of Ocean Outfalls

In this section, the potential risk model expressed by the conceptual model is tested using actual data from existing ocean outfalls or the SEFLOE studies. As part of the risk analysis, the following questions will be answered:

- Do plausible exposure pathways exist for receptors to be exposed to stressors?
- Are concentrations of stressors high enough to potentially cause adverse effects?
- Is there evidence for adverse effects in receptors caused by exposure to stressors derived from treated wastewater effluent?

6.6.1 Evaluation of Physical Transport

In order to appreciate the large-scale risk setting, it is important to understand physical environmental risk factors. These are the physical features of the environment that play a significant role in the risk of a particular wastewater management option. A thorough understanding of physical oceanography, circulation, mixing, dispersion, and dilution of the discharged effluent plume at the ocean outfalls is necessary for evaluating the physical environmental risk factors associated with ocean outfalls.

The SEFLOE studies and other related studies provide much of the information needed to assess such risk factors. Intensive cruises were conducted to each outfall during winter and summer to detect and track, using acoustic measurements, the initial plume and to develop two-dimensional models of the effluent plumes. To map and model current velocities and water column structure, moored current monitors were deployed near outfall discharge sites for several periods between August 1991 and October 1992. An acoustic Doppler current profiler was deployed at the Miami-Central outfall diffuser in the summer of 1992 to obtain more information on current regimes and depth variations in currents. Dye and salinity tracking were also used to map the distribution and movements of water masses. Water-column characteristics (conductivity, temperature, and depth, or CTD) were measured using CTD water-column profiling on a semimonthly basis at each outfall from July 1991 to October 1992 (except months when intensive cruises were underway). Physical characteristics of the surfacing effluent plumes were monitored using towed CTDs. Initial and subsequent dilutions were estimated, using differences in salinity between the effluent and ambient seawater as a tracer.

The SEFLOE studies also collected water-quality information from the effluent plume and from ambient seawater. Parameters measured included bacteria (total coliforms, fecal coliforms, and *Enterococcus* bacteria), nutrients (ammonia, total Kjeldahl nitrogen (TKN), total phosphorus, nitrate, nitrite), oil and grease, 126 priority pollutants, and total suspended solids (TSS). Effluent samples from the six wastewater treatment facilities were also analyzed for salinity, bacteria, nutrients, priority pollutants, oil and grease, $CBOD_5$, and TSS.

6.6.1.1 Transport, Dispersion, and Dilution by Currents

Transport, dispersion, and dilution of effluent plumes by ocean currents and circulation are critical risk factors for evaluating potential risks of ocean outfalls. The direction and speed of current flow, which together determine current velocity, are critically important risk factors. The faster the current speed is at the outfall, the greater the rate at which the plume is dispersed and diluted by ambient seawater, and the lower the concentration of stressors. Conversely, the slower the current speed is at the outfall, the lower the rate at which the plume is dispersed and diluted by ambient seawater, and the higher the concentration of stressors remaining in the area. The direction of current flow, away from or towards human or ecological receptors, is also important to characterize. Current flow towards the coast will increase the likelihood that coastal receptors (human or ecological) will be exposed to effluent constituents, while current flow away from the coast will decrease the likelihood of exposure.

The SEFLOE II study provided an extensive set of current measurements and water-column density profiles, using a combination of acoustical backscatter and direct sampling methods. Information on water quality of the effluent plume and ambient seawater also was obtained. Analysis of the current data from the four outfall locations indicated that three major current regimes, characterized by different flow directions, were present at all outfall sites:

- *Current Regime i* = Northerly flows, thought to be associated with western meanders of the Florida Current
- *Current Regime ii* = Southerly flows, which are part of an extensive eddy current
- *Current Regime iii* = Rotary-like flow, which consists of groups of rotations interspersed between northerly and southerly flows. The rotations were irregular and temporally fleeting, with durations of 5 to 8 hours.

Current Regime *i* predominates, displaying rapid current flow in a northerly direction throughout the entire water column. The SEFLOE II study reports that this current flow occurs approximately 60% of the time. Current Regime *ii*, representing southerly flow, occurs approximately 30% of the time. Current Regime *iii*, representing flow in other directions (easterly, westerly) occurs irregularly and less than 10% of the time, and the duration of such flows is very short (5 to 8 hours).

To estimate the percentage of time that Current Regime *iii* flows to the west, data points reflecting current direction at a depth of 16.8 m at the Miami-Dade Central District wastewater treatment plant (Hazen and Sawyer, 1994) were visually analyzed. It was assumed that, as described in the SEFLOE II report, easterly and westerly flows occur a total of 10% of the time. This analysis indicates that westerly flows occur approximately 4% percent of the time, while easterly flows occur approximately 6% percent of the time. Data sets using an Aanderaa current meter and using an acoustic Doppler current profiler yielded equivalent results.

The Florida Current in the vicinity of the ocean outfalls can be characterized as a fast-flowing current, with speeds ranging from approximately less than 5 centimeters per second (cm/sec) to maximum speeds of over 60 to 70 cm/sec. In general, the mean current velocity observed during Regime *i* northerly current flow is greater than any other current regime, while the mean current velocity of Regime *iii* rotary-like flow is the lowest (Hazen and Sawyer, 1994). Because the dilution of the effluent plumes is a function of current velocity, the Regime *iii* rotary-like flow will result in the higher concentration of stressors.

For the purposes of evaluating plume dispersal, the SEFLOE II report used the lowest 4-day average current speeds and the lowest 10th-percentile average current speeds as conservative (that is, protective) estimates of average current speeds. These current speeds are shown in Table 6-4 (Hazen and Sawyer, 1994). The maximum current speeds recorded during the study are shown for comparison. In general, the average current speeds are highest at the Broward outfall.

Table 6-4. Average Current Speeds (cm/sec)

Outfall	Lowest 4-Day Average Current Speed	Lowest 10th-Percentile Average Current Speed	Maximum Current Speed
Broward	15.7	12.3	> 70
Hollywood	13.7	7.8	> 60
Miami-Dade North	13.2	7.7	> 70
Miami-Dade Central	13.6	11.6	> 70

Source: Hazen and Sawyer, 1994.

Irrespective of which current regime was predominant, current direction was generally the same at all depths, based on water column profiles. Slight variations in current speed occurred throughout the water column, with higher speeds occurring near the ocean surface.

6.6.1.2 Dilution of the Effluent Plume

The SEFLOE I study characterized dilution of the effluent plumes at all six of the ocean outfalls, using dye and salinity data and acoustic backscattering methods. Based on these studies, the effluent plume typically has three distinct phases:

1. The initial dilution phase commences when the effluent leaves the outfall pipe and lasts until the effluent reaches the surface of the ocean.
2. The near-field dilution phase commences when the plume reaches the surface and undergoes radial dispersion because of the momentum of the rising effluent

within the upper 3 m of the ocean surface. This phase is visible on the surface of the ocean as a feature that is often called a “boil.”

3. The farfield dilution phase is characterized by an effluent plume that has undergone dilution during the initial and near-field dilution phases and is further dispersed by surface currents.

The characteristics of each of these dilution phases are discussed below.

Initial and Near-Field Dilution

Because the water samples are collected at or near the boil, within 1 m of the surface, the sampling actually is conducted within both the initial and near-field dilution phases, as defined above in the SEFLOE study. Therefore, these two dilution phases are discussed together in this section.

Initial dilution using tracer dye methods and chlorine was defined in the SEFLOE study as the ratio of measured concentrations of the dye in the effluent boil to the initial concentration of the dye in the effluent at the treatment facility. The initial dilution that occurs over a 4-day period at a conservative current speed (worst-case scenario with the lowest average current speed) is described in Table 6-5 below as the flux-averaged initial dilution factor. The greater this factor is, the higher the dilution.

Table 6-5. Flux-Averaged Initial Dilution of Effluent Plume.

Ocean Outfall	Lowest 4-day Average Current Speed (cm/s)	Flux-Averaged Initial Dilution Factor
Broward	15.7	43.3
Hollywood	13.7	28.4
Miami-Dade North	13.2	50.1
Miami-Dade Central	13.6	28.3

Source: Hazen and Sawyer, 1994, Table III-5.

The initial dilution factors from the SEFLOE studies indicate that initial dilutions were highest for the Miami-Dade North ocean outfall and lowest for the Miami-Dade Central and Hollywood outfalls. Yet, according to Table 6-5, Miami-Dade North outfall had the lowest 4-day average current speed. The high initial dilution at this outfall may explained by the use of multiport diffusers at the Miami-Dade North outfall. The use of multiport diffusers at the Miami-Dade North outfall appears to aid in dispersal of the effluent plume over a wider area, thereby decreasing potential risk. However, these effluent plumes were diluted at slower rates than the effluent plumes from the Hollywood and Broward outfall plumes, according to Englehardt et al. (2001).

The rate of initial dilution of the effluent also is largely dependent upon the current speed and the rate of discharge of effluent from the outfall. As current speed increases, dilution also increases. As the rate of effluent discharged from the outfall increases, the rate of dilution increases. These relationships are shown in Figure 6-5, which shows flux-averaged dilution vs. current speed for effluent discharged from the Miami-Dade Central ocean outfall (from Hazen and Sawyer, 1994).

At a lower current speed of 10 cm/sec at a 253 mgd discharge rate, the dilution factor is approximately 20; at a higher current speed of, say, 60 cm/sec, the dilution factor is over 40. Also, for a given current speed, at higher discharge rates (that is, 253 mgd), the dilution is lower than if effluent is discharged at a lower rate (that is, 115 mgd).

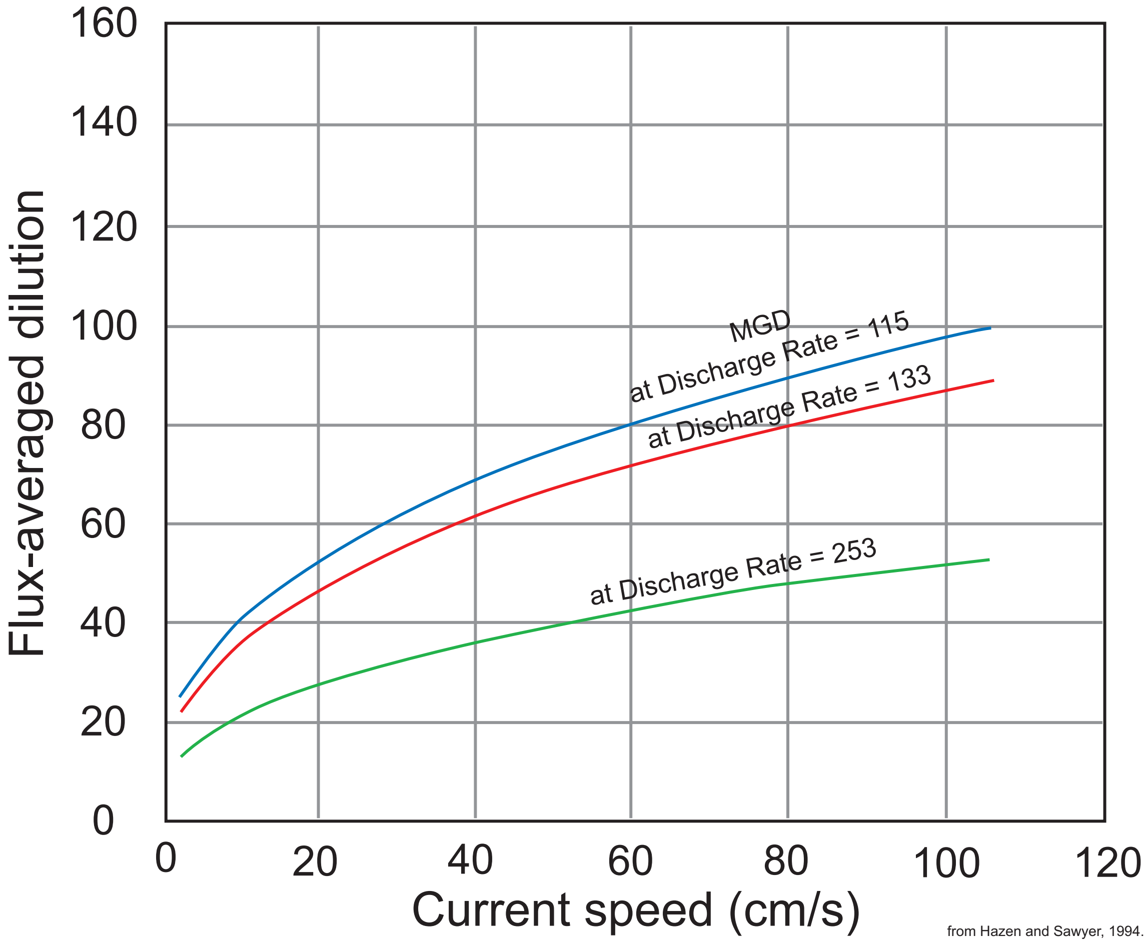
The SEFLOE study found that normally surfacing plumes were present at all outfalls throughout the year, even in summer months when density stratification of the water column was weak. It is noteworthy, however, that during several strong stratification events, portions of rising plumes were trapped and prevented from freely dispersing, based on acoustic profiling conducted by John Proni and colleagues (Proni et al., 1996, 1994; and Proni and Williams, 1997). In such areas of plume trapping, effluent constituents were present at relatively higher concentrations than in areas in which there was no such trapping and the effluent was freely dispersed. Concentrations of effluent constituents were, however, quite low, but their existence is quite significant. Definitive measurements of dilution in trapped plumes are planned for an upcoming SEFLOE III study (John Proni, personal communication). Plume trapping during strong stratification events therefore represents one potential risk factor.

Farfield Dilution

The SEFLOE II report indicates that measurements of farfield dilutions were the most difficult field measurements to obtain. Measurements of salinity, dye concentration, and acoustic backscatter intensity were used simultaneously for dilution calculations and to guide sampling for biological and chemical parameters for subsequent dilution determinations. Subsequent dilution is defined in the SEFLOE report as dilution that occurs as plume elements move away from the boil location, which represents the initial dilution and near-field dilution phases.

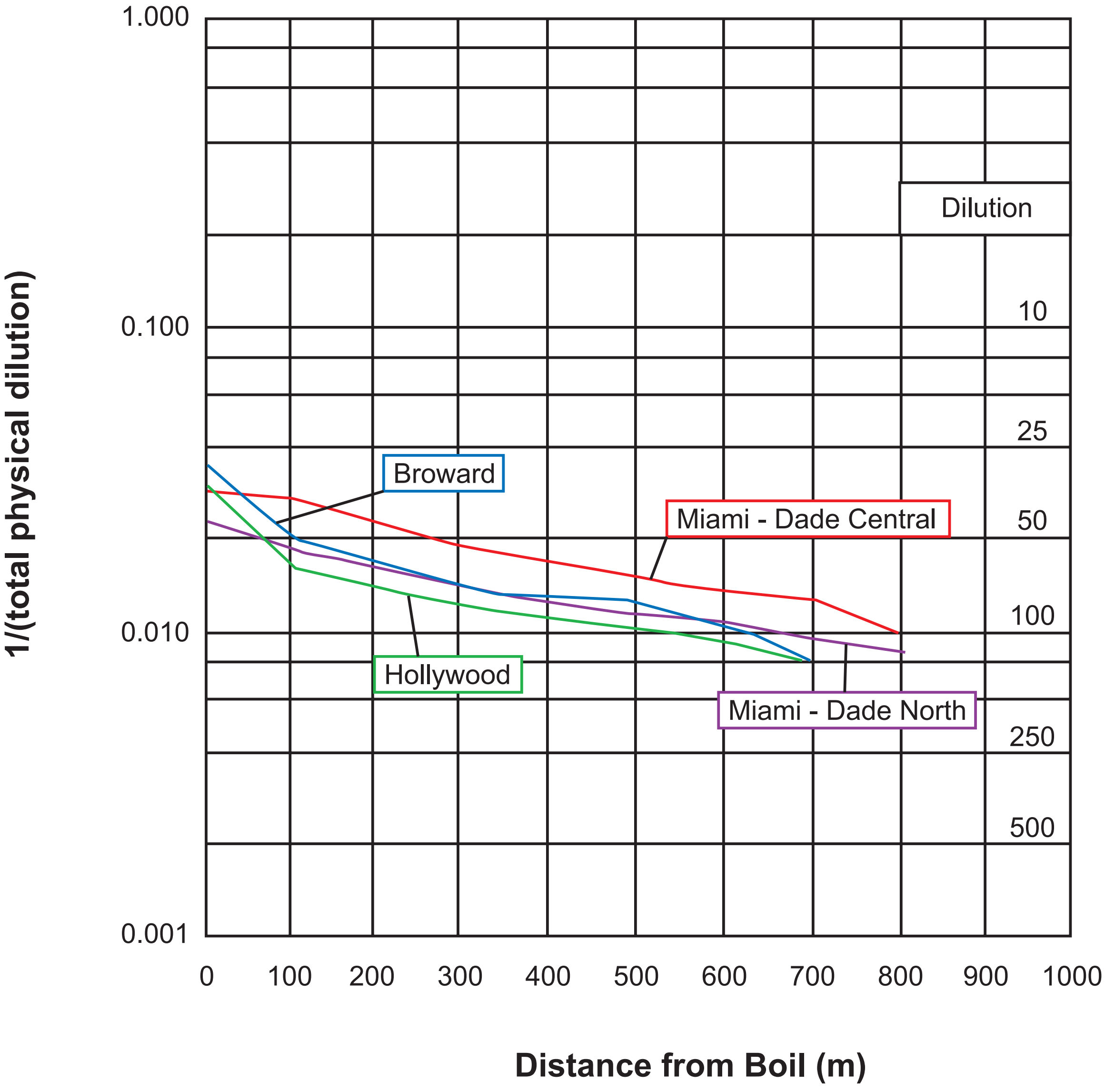
Average subsequent dilutions in the near-field and farfield for the four ocean outfalls are compared in Figure 6-6, which plots the inverse of total physical dilution (1/total physical dilution) of the plume on a logarithmic scale against the distance from the boil in meters (from Hazen and Sawyer, 1994, Figure III-77). On this plot, as one moves away from the boil, dilution increases. Figure 6-6 shows the following:

- Treated effluent discharged from the Broward and Hollywood outfalls experiences more rapid dilution in the 0- to 100-m range than the effluent discharged from the two Miami-Dade outfalls. These two outfalls have larger diameter ports than the other ocean outfalls (see Table 6-1).
- Between 100 and 200 m from the plume boil, there is a change in the rate of dilution, suggesting that buoyancy spreading and positive buoyancy of the plumes is still occurring at this distance from the outfall.



from Hazen and Sawyer, 1994.

Figure 6-5. Initial Dilution as a Function of Current Speed and Discharge Rate (Miami-Dade Central Outfall)



Source: Hazen and Sawyer, 1994

Figure 6-6. Total Physical Dilution as a Function of Distance from the Boil (Four Ocean Outfalls)

- Between 100 m and 400 m from the boil, total physical dilution with distance curves are approximately similar for both current Regimes *i* (northerly flow) and *ii* (southerly flow), with average dilutions ranging from approximately 60:1 to 90:1 at a distance of 400 m from the boil location.
- Dilution rate increases slightly at 500 m from the boil for Broward, 700 m from the boil for Miami-Dade Central, and 600 m from the boil for Hollywood outfalls. The effluent plume from the Miami-Dade North outfall shows steady dilution throughout nearly the entire distance sampled.

Note that the 400-m mixing zone equates to the 502,655 m^2 maximum mixing zone size for open ocean outfalls regulated by the state of Florida. Dilutions ranging from 60:1 to 90:1 were used to evaluate the concentrations of the measured constituents of concern in wastewater and were compared to the Class III standards.

The information from the SEFLOE studies indicates that overall dispersal and dilution of the discharged effluent occurs rapidly, within hours to days, and that the mixture of effluent and receiving water rapidly achieves background or near-background concentrations of tracer dyes and salinity within 400 to 600+ m of the outfall. Rapid dispersal results in dilution of the effluent and therefore reduces the risk of exposure to undiluted effluent.

6.6.2 Evaluation of Stressors, Exposure Pathways, and Receptors

In this section, information from the SEFLOE studies and other studies are used to evaluate the following risk questions posed by the conceptual model:

- Do concentrations of stressors exceed standards intended to protect human health or ecological systems?
- Is there evidence that human or ecological receptors are exposed to or take up stressors derived from the treated effluent or secondary stressors that are created by discharge of effluent?
- Is there evidence of adverse effects on human or ecological receptors in the vicinity of the outfalls?
- If there are adverse effects that can be attributed to the use of ocean outfalls, are these effects reversible?

6.6.2.1 Pathogenic Microorganisms

Pathogenic Microorganisms in Unchlorinated Effluent as a Worst-Case Scenario

The SEFLOE study measured three types of bacteria indicative of mammalian wastes: total coliforms, fecal coliforms and *Enterococcus*. Samples for microbiological analysis were taken from both secondary treated unchlorinated effluent and from within the effluent plume itself (Hazen and Sawyer, 1994). Based on these measurements and the effluent plume characteristics, SEFLOE provided recommendations to regulators concerning the width of the mixing zones that would have to be defined to allow dilution of the effluent to meet Florida water-quality criteria for bacteria.

Recommendations on the maximum allowable concentrations of bacteria in effluent were also provided to help guide treatment plant operators in determining the correct amount of chlorine to use in disinfecting effluent. Florida regulations require basic disinfection to meet a standard of 200 fecal coliforms per 100 mL of treated wastewater. However, because chlorine disinfection itself can create unwanted chlorinated byproducts (for example, trihalomehanes) and pose potential health or environmental risks, the regulations also allow for an effluent mixing zone range. This allows dilution of effluent, reducing the amount of chlorine used, while still meeting water-quality standards. SEFLOE's recommended widths of mixing zones of unchlorinated effluent to achieve Class III bacterial water quality standards are summarized in Table 6-6.

Table 6-6. Recommended Mixing Zone Ranges for Unchlorinated Effluent, Using Different Methods of Calculating Bacterial Concentrations

Facility	Radial Distance (m)			
	Maximum Single Requirement	Percent Not Greater Than Requirement	Geometric Mean Requirement	Range of Controlling Criterion
Broward County	900	900	400	900
Total coliform	800	800	400	800
Fecal coliform	800	800	400	800
Enterococci	900	900	400	900
City of Hollywood				
Total coliform	500	800	0	80
Fecal coliform	200	700	0	700
Enterococci	1,000	800	400	1,000
Miami-Dade North				
Total coliform	900	900	400	900
Fecal coliform	900	900	400	900
Enterococci	1,000	1,000	800+	1,000
Miami-Dade Central				
Total coliform	Uncertain	Uncertain	800	Uncertain
Fecal coliform	900	900	800+	900
Enterococci	Uncertain	Uncertain	800+	Uncertain

Note: Data from Miami-Dade Central are shown as uncertain because of suspected high background concentrations of indicator bacteria from the Miami River.
Source: Hazen and Sawyer, 1994.

Because these values represent distances that the unchlorinated effluent would have to travel before the concentration of bacteria became diluted to background levels, they provide information for an evaluation of one potential worst-case risk scenario, which is failure of chlorination to treat secondary effluent to meet Class III water-quality standards. In general, the results show that even if unchlorinated effluent were discharged, it would become dilute enough to meet Class III bacteriological water quality standards within 800 to 900 m of the outfall or, in some cases, much closer.

Disinfection To Achieve Microbial Standards

The Florida regulations require a mixing zone area of up to 502,655 m^2 to allow dilution of the effluent to Class III water-quality standards. Although the Florida regulations do not require that a circular mixing zone be established, and in fact do not specify a shape, the use of a circular mixing zone for evaluating whether dilution achieves the standards makes it easier to compare actual versus expected concentrations of effluent constituents. Such a circular mixing zone would have a radius of 400 m. It is worth noting, however, that a circular mixing zone would occur only in an environment where there is no current flow.

To assist facility operators in determining how to manage bacteria to meet Class III regulatory standards, SEFLOE provided calculations of the maximum allowable numbers of indicator bacteria in effluent within 400 m of the outfall. These calculated concentrations are shown in Table 6-7. They include assumptions concerning microbial attenuation processes that are not based solely on physical dilution alone (John Proni, personal communication). These bacterial numbers provide wastewater treatment facility operators with specific bacterial concentration goals to meet, using chlorination of effluent in order to meet Class III water-quality standards. The 800-m mixing zone is included because, as stated above, the mixing zone is not required to be a circular mixing zone but instead is an area, and the effluent plume may well extend outside of the 400-m-radius zone.

Table 6-7. Maximum Allowable Concentrations of Indicator Bacteria in Effluent within Different Mixing Zones

Facility	0 m Initial Dilution Zone	400 m Mixing Zone	800 m Mixing Zone
Broward County			
Total coliform	302	3,388	10,471
Fecal coliform	72.6	437.6	935
Enterococci	--	284	53
City of Hollywood			
Total coliform	575	2,884	3,631
Fecal coliform	296	324	1626
Enterococci	7.3	38.4	106
Miami-Dade North District			
Total coliform	3,715	14,454	28,840
Fecal coliform	1,517	20,465	7,962
Enterococci	153	840	879
Miami-Dade Central District			
Total coliform	186	417	11,000
Fecal coliform	68	252	1,910
Enterococci	2.4	29.0	334.0

Note: All bacterial numbers = 100 per 1000 mL
Source: Hazen and Sawyer, 1994, Table III-17.

Proximity of Effluent Plume to Coastal Receptors

One significant microbiological risk factor is the proximity of the ocean outfalls to land and to potential terrestrial and nearshore receptors. If one assumes that the required mixing zone area of 502,655 m^2 is translated into a circle of radius 400 m centered on the outfall, one can compare this with the actual distance of the outfall from land (Table 6-8). This table indicates that the highest risk outfalls, solely in terms of distance from shore, are the Del Ray Beach and Boca Raton outfalls, while the lowest risk outfall in terms of distance is the Miami-Dade Central outfall.

Table 6-8. Comparison of Circular Mixing Radii for Effluent and Outfall Distance from Shore (m)

Parameter	Miami-Dade Central District	Miami-Miami-Dade North District	City of Hollywood	Broward County	Delray Beach	Boca Raton
Distance offshore	5,730	3,350	3,050	2,130	1,600	1,515
Distance from 400 m circle to land	5,330	2,950	2,650	1,703	1,200	1,115
Distance from 800 m circle to land	4,930	2,550	2,250	1,330	800	715

Note: A 400-m mixing radius is required for chlorinated effluent to meet Class III bacteriological standards. If the effluent is unchlorinated, an 800-m mixing radius is required.
Source: Hazen and Sawyer, 1994.

It is important to note that in reality the effluent plumes do not disperse equally over a circular area, as implied by the circular mixing zone calculations used by the SEFLOE study, but are instead dispersed by the strong Florida Current to form an extended plume, whose longest dimension is aligned with the northerly flowing Florida Current. It is not known what would happen if the northerly current flow were to weaken or disappear. It is probable that, for such a major change in the Florida Current to occur, there would have to be major changes in ocean circulation elsewhere as well.

There are a number of gaps in information concerning human health and ecological risks from pathogenic microorganisms remaining in treated effluent. The SEFLOE studies of enteric microorganisms in effluent and the dilute effluent plume did not include measurements of *Cryptosporidium* or *Giardia*. Other enteric viruses and bacteria were not measured. Ecological risks posed by effluent microorganisms could not be evaluated in this report because of the lack of long-term monitoring studies of benthic organisms in the effluent plume track or adjacent waters.

Human health risks posed by effluent microorganisms also could not be evaluated directly because of the lack of information on pathogenic microorganisms in coastal waters adjacent to the outfalls and derived from the outfalls. Beach water-quality information would provide information on microbial concentrations, but would not distinguish between onshore versus offshore sources of pathogenic microorganisms. Many onshore sources of pathogenic microorganisms undoubtedly exist in southeast

Florida, from a combination of intensive urban and agricultural activities. To distinguish between these different sources, a tracer study involving microbial tracers or combined microbial/chemical/biochemical tracers would have to be conducted. However, it remains clear that there is a risk from pathogenic protozoans such as *Cryptosporidium*, which is not addressed by chlorination, and that the risk is highest during the westward-flowing current phase, which occurs approximately 4% of the time.

Nevertheless, the SEFLOE studies provide a significant body of knowledge for risk managers to understand the processes that affect microbiological risks to human health. They also provide specific recommendations concerning the level of dilution and disinfection of treated wastewater needed to achieve Class III water-quality standards for microbial indicators of wastewater (fecal coliforms, *Enterococcus*, total coliforms) at a hypothetical 400 –m-radius mixing zone. Although the SEFLOE studies do not provide follow-up monitoring to confirm that these standards are indeed met all of the time, monitoring of chlorinated treated wastewater at treatment facilities suggests that these microbial standards for regulated pathogens and indicator bacteria are nearly always met.

6.6.2.2 Nutrients

There are three questions that must be addressed in order to evaluate potential risks from nutrients in the secondary treated effluent:

- Are nutrient levels in the effluent higher than ambient water or applicable marine water-quality standards to protect ecological health?
- Is there evidence that nutrients from the treated effluent are taken up by phytoplankton and microalgae and then converted to biomass?
- Is there evidence of ecological effects from nutrient inputs from the effluent plume?

To evaluate ecological risks associated with nutrient discharge, information on effluent nutrient concentrations was compared with Florida water-quality standards designed to protect aquatic ecosystems. The Class III Florida water-quality standards state, “In no case shall nutrient concentrations of a body of water be altered so as to cause an imbalance in natural populations of aquatic flora or fauna.” Therefore, it is also valuable to compare nutrient concentrations in secondary treated effluent with nutrient concentrations in ambient seawater at the site, because natural populations of organisms will be adapted to the ambient concentrations and may experience changes if nutrient concentrations change.

Table 6-9 compares the nutrient concentrations in secondary effluent, ambient seawater, and 400 m and 800 m mixing zones at three ocean outfalls (from Hazen and Sawyer, 1994, Tables III-18, III-19 and III-20). All values in the table are from Hazen and Sawyer (1994) unless otherwise noted as calculated for this report. The 800 m mixing zone is included as a conservative approach.

Table 6-9. Nutrient Concentrations in Secondary Treated Effluent, Ambient Water, and 400 m and 800 m Mixing Zones for Three Ocean Outfalls

Parameter	Ammonia (mg/L)				Nitrate (mg/L)				Total Phosphorus (mg/L)			
	Mean	Max.	No. of Samples	Other Values	Mean	Max.	No. of Samples	Other Values	Mean	Max.	No. of Samples	Other Values
Broward												
Ambient water	0.09	0.5	28		0.16	0.16	1		0.08	0.16	17	
Effluent	12.48	20.0	42	8.7[d]	0.42	1.08	7	0.64[a], 9.6[b], 0.28[c] 3.8[d]	1.66	2.45	43	1.33[d]
Boil	0.35	0.9	55		0.12	0.46	9		0.18	0.84	41	
400 m	0.13	0.35	32		0.02	0.02	1		0.10	0.3	25	
800 m	0.11	0.5	26		0.01	0.01	1		0.10	0.13	21	
Dilution at 400 m**	96x				21x				16.6x			
Dilution at 800 m**	113x				42x				16.6x			
Hollywood												
Ambient water	0.09	0.14	8		0.11	0.11	9		0.09	0.11	6	
Effluent	5.96	14.00	31		1.70*	1.60*	31		0.97	1.60	32	
Boil	0.25	0.80	15		0.16	0.52	15		0.11	0.40	12	
400 m	0.09	0.12	4		0.12	0.30	4		0.10	0.10	2	
800 m	0.09	0.12	4		0.11	1.40	3		0.10	0.10	3	
Dilution at 400 m**	66x				14x				9.7x			
Dilution at 800 m**	66x				15.5x				9.7x			
Parameter	**Ammonia (mg/L)**				**TKN (mg/L)**							
	Mean	**Max.**	**No. of Samples**	**Other Values**	**Mean**	**Max.**	**No. of Samples**	**Other Values**				
Miami-Dade North												
Ambient water	0.66	1.96	4		0.72	2.24	14		--	--	--	
Effluent	10.46	13.7	11		13.4	17.4	11		--	--	--	
Boil	0.56	2.24	10		0.6	3.64	28		--	--	--	
400 m	0.10	0.15	2		0.19	0.4	9		--	--	--	
800 m	0.38	0.84	4		0.61	1.96	13		--	--	--	
Dilution at 400 m**	105x				71x							
Dilution at 800 m**	28x				22x							

* These values are listed here as reported in the SEFLOE II report (Hazen and Sawyer, 1994).

** Calculated for this report using the ratio of observed concentration at the distance indicated to the initial concentration in effluent.

[a] = Miami-Dade North District, 1999. See Appendix Table 1-2.

[b] = Brevard County (South Beaches WWTF), 2000. See Appendix Table 1-2.

[c] = Albert Whitted WRF, St. Petersburg. See Appendix Table 1-2.

[d] = Mean value from Englehardt et al. (2001), compiled from several sources. See Appendix Table 1-2.

These data indicate that there are site-specific differences in whether or not the effluent nutrients become diluted to background levels by the time the effluent water reaches a distance of 800 m from the outfall. For example, at Broward, the average ammonia concentration in the plume did not reach ambient levels at 800 m. The average nitrate concentrations in the boil did not exceed background concentrations at the boil, although there are individual boil values which exceed background (John Proni, personal communication). Average total phosphorus in the plume did not reach background concentrations at 800 m.

There is also considerable variability in the concentrations and data as well; for example, the background value for nitrate is 0.16 mg/L based on 1 measurement, while the mean concentration of nitrate at the boil is 0.12 mg/L (9 measurements) and the concentration of nitrate at 400 m is 0.02 mg/L (1 measurement). Differences in time of sampling could account for these differences, as well as natural variability.

At the Hollywood outfall, average ammonia concentrations in the effluent plume reached background levels at 400 m, perhaps partly because the initial effluent concentration of ammonia was lower than at Broward. Nitrate concentrations in the plume did not reach background concentrations until 400 m out from the outfall. Total phosphorus did not reach background concentrations even at 800 m, similar to the Broward outfall.

At the Miami-Dade North outfall, ammonia at the boil did not exceed background concentrations. Concentrations of nitrate and phosphorus at this location were not reported in the SEFLOE study.

The calculated dilutions at 400 m and 800 m indicate that there are differences in dilution of ammonia, nitrate, and total phosphorus as the effluent plume becomes dispersed. Ammonia appears to dissipate most rapidly, nitrate may or may not become diluted to background concentrations at a distance of 400 m, and total phosphorus may not become diluted to background concentrations even at a distance of 800 m from the outfall. These differences in dilution may be from the differences in chemical behavior, natural variability in concentrations, differences in sampling time or location, or a combination of all of these factors.

The variability in dilution factors calculated using measurements of nutrient concentrations do provide an illustration of how the actual behavior of wastewater constituents (for example, nutrients) as measured *in situ* at a given time may deviate from the ideal modeled dilution factors, even if the modeled dilutions are based on the use of actual data on distributions of conservative tracers such as salinity, dyes, or density. To do a detailed analysis of nutrient dilution as the effluent plume moves further from the outfall, a specific study designed to track nutrient concentrations and composition would need to be conducted. Such a study should examine all inorganic and organic phases of nitrogen and phosphorus, as well as use stable isotope tracers to track effluent nitrogen and organic matter. The same is true for dissolved organic matter, which is not addressed in the SEFLOE study. The physical oceanographic conditions present during such a study would have to be documented as well, since it would be highly possible for dynamic changes in local current flow to disrupt an otherwise orderly plume tracking experiment. It should be noted that nutrient fate and transport was not a focus of the SEFLOE studies as reported in Hazen and Sawyer. A study of nutrient fate and transport, based on the use of stable isotope tracers, is described below (Hoch et al., 1995).

At the time of the SEFLOE II studies, there was concern that nutrients from the discharge of wastewater into the open ocean was causing enhanced growth of *Codium*, an algae observed in 1991 and 1992 on several southeast Florida coral reefs. The SEFLOE II reports gives several reasons as to why the nutrients discharged from the outfalls are not likely to cause increases in *Codium* (Hazen and Sawyer, 1994), as summarized below:

- *Codium* plants require attachment to a solid substrate in order to grow, while the outfall plume rises. Thus, *Codium* habitat is not exposed directly to the effluent plume.
- Attached *Codium* plants were not present near the outfall sites where nutrient levels are above background-seawater levels.
- *Codium* attaches to solid substrate in deeper waters, outside of the nutrient dispersal area associated with the outfalls. The effluent nutrient levels quickly reach background concentrations within a short distance of the outfall (typically several hundred meters).
- Natural cycles of *Codium* growth have been reported in the literature prior to the discharge of wastewater effluent to the open ocean.
- The sporadic occurrences of the algal blooms are not consistent with the uniform discharge of the effluent, indicating no significant relationship.

The SEFLOE summary states that, “While the introduction of nitrogen into the marine environment can have significant impacts on water quality and wildlife, in this case the impacts to the open ocean appear to be mitigated by the vast reservoir of water available for dilution, the speed with which dilution occurs due to the currents at the Floridian outfalls, and the uptake and removal of nitrate by phytoplankton which entrains the nitrogen into the food chain, thereby removing it from the area where it was first emitted. The rapid dilution and removal of nitrate from the area immediately surrounding the boil quickly decreases any measurable ecological risks associated with the discharge of nitrate into the open ocean at the point where the effluent meets the receiving waters.”

The stable isotopic composition of nitrogen in organic matter, called $\delta^{15}N$, can be useful in distinguishing the sources of organic matter and nutrients and the trophic level of the organisms producing the organic matter (Hansson et al., 1997; Peterson, 1999). Wastewater nitrogen tends to be isotopically enriched in the heavier isotopes of nitrogen relative to the atmospheric nitrogen standard, which represents a pristine source of nitrogen. Sewage effluent nitrogen is often isotopically heavier (more positive numbers) because of isotopic fractionation along the food chain that results in higher trophic levels, producing isotopically heavier nitrogen in wastes (LaPointe, 1997; Densmore and Bohlke, 2000; Rau et al., 1981; Schroeder et al., 1993; Spies et al., 1981; Spies, 1984; Van Dover et al., 1992). Wastewater nitrogen has been implicated as a source of isotopically heavier nitrate in the Florida Keys (LaPointe, 1997). Carbon ($\delta^{13}C$) and sulfur

(δ^{32}S) also provide useful isotopic tracers for organic matter (Fry et al., 1998; Gearing, 1988; Gearing et al., 1991; Wainwright and Fry, 1994; Peterson et al., 1996; Peterson, 1999).

LaPointe et al. (1992) suggests that phosphorus may be of greater importance than nitrogen as a limiting nutrient in macroalgal growth in carbonate-rich tropical waters, while nitrogen is more important in siliciclastic systems. More recently, work by LaPointe (1997) found that, at four sites located between West Palm Beach and Hobe Sound approximately 2 to 3 kilometers offshore, waters enriched with dissolved inorganic nitrogen (DIN) increased the photosynthetic efficiency of *Codium isthmocladum* in southeast Florida waters. In addition, elevated δ^{15}N values of *C. isthmocladum* tissue indicated that wastewater dissolved in DIN was a source of nitrogen to blooms in southeast Florida. LaPointe found that increases in δ^{15}N values in *Codium* tissue of more than 10 parts per thousand (*o/oo*) occurred with the onset of the rainy season, suggesting that discharges during the rainy season provided a significant nitrogen source.

A different study of the fate of sewage effluent-derived nitrogen and carbon using stable isotope tracers was conducted by researchers from EPA and Texas A&M University (Hoch et al., 1995). This study examined suspended particulate organic matter, sediment organic matter, filter-feeding organisms (sponges, soft, or gorgonian corals), settling particle fluxes, and dissolved nutrients (ammonia, nitrate and nitrite, phosphorus, and organic carbon) in the vicinity of the six southeast Florida ocean outfalls and one small outfall located in the Florida Keys. The study hypothesized that pelagic suspended organic matter composed of phytoplankton is a source of organic matter to benthic ecosystems and sediments and that the isotopic composition of these phytoplankton sources (and the nutrients they utilize) would be reflected in the isotopic composition of organic matter in sediments.

Hoch et al. (1995) found that sewage effluent ammonia from the southeast Florida outfalls had δ^{15}Ns ranging from 4.4*o/oo* at the Central Miami-Dade outfall, to 8.6*o/oo* at Broward and 15.4*o/oo* at Key West. Sewage effluent DIN ranged from 4.3*o/oo* to 8.1*o/oo* to 12.7*o/oo*, respectively. Nitrate and nitrite together had δ^{15}Ns ranging from –1.6*o/oo* to –5.7*o/oo* to 10.5*o/oo*, respectively. In comparison, suspended particulate organic matter (including phytoplankton that take up nutrients) had δ^{15}Ns that were more negative than effluent DIN and more similar to ambient marine organic matter (2*o/oo* to 4*o/oo*). This suggests that the effluent plume nitrogen was being diluted with ambient marine suspended particulate organic matter. In general, the nitrogen isotopic composition of ammonia and DIN at the Central Miami-Dade outfall was not very different from that of ambient marine organic matter and DIN, while ammonia and DIN from the Broward plant had isotopic signatures significantly different from that of ambient marine organic matter.

The results for the six southeast Florida ocean outfalls indicated that phytoplankton uptake of effluent-derived nitrogen into biota was not clearly demonstrated at any of the southeast Florida outfalls, including the largest outfalls (Broward and Central Miami-

Dade). At these outfalls, there appears to be little coupling between the pelagic and benthic ecosystems, even though loading of sewage effluent-derived nitrogen to coastal environments was significant (about 6 x 10^6 kg of total N per year, of which more than 97 percent is derived from the six southeast Florida outfalls). Furthermore, the measured rates of primary production were less than production estimated from the nitrogen load. Hoch and colleagues concluded that the strong currents and rapid dilution at the southeast Florida outfalls may have caused rapid dilution of sewage effluent nitrogen prior to uptake by plankton. An alternate explanation for the observed isotopic values of organic matter is that phytoplankton may have taken up a form of nitrogen not measured isotopically (for example, organic nitrogen) (Hoch et al., 1995).

In contrast, the same study found that, at the Key West outfall, a conservative estimate of the amount of effluent particulate carbon contributing to the diet of soft corals immediately adjacent to the outfall is about 40%, based on the use of both carbon and nitrogen stable isotopes. These different results suggest strongly that the physical dispersion and dilution of effluent along the southeast Florida coast plays a major role in reducing the ecological significance of effluent nitrogen. However, it also suggests that the use of stable isotopes may not be an extremely sensitive tracer if the sewage effluent isotopic composition is not significantly different from ambient marine organic matter to begin with (Hoch et al., 1995).

6.6.2.3 Metals and Organic Compounds

As with nutrients, there are three basic questions concerning potential effects of metals and organic priority pollutants remaining in effluent following secondary treatment:

- Are concentrations of priority pollutants in effluent or diluted effluent higher than water-quality standards for protection of ecological health?
- Can biological uptake of priority pollutants be demonstrated for any ecological component?
- Is there evidence of adverse effects because of exposure to or uptake of priority pollutants?

Metals

To address the question of whether metals in undiluted and diluted effluent meet water-quality standards, the SEFLOE studies measured priority pollutant metals and detected several (copper, arsenic, silver, lead) and cyanide in undiluted effluent. Concentrations sometimes exceeded Class III marine water-quality standards (Table 6-10). None of the metals tested in undiluted effluent exceeded the Florida Maximum Allowable Effluent Levels (Hazen and Sawyer, 1994).

Table 6-10. Priority Pollutant Metals Detected in Treated Wastewater Effluent Exceeding Class III Marine Water-Quality Standards

Metal	Concentration in Treated Effluent (µg/L)	Background Concentration in Oceans[a] (µg/L)	Florida Maximum Allowable Effluent Level (µg/L)	Florida Class III Marine Water Standards (µg/L)	EPA Saltwater Criteria (µg/L)	Dilution To Meet Most Stringent Criteria
Broward						
Arsenic, total	BDL, **124**, <1.70, 2.3	1.77	N/A	≤ 50	36	3.6
Copper, total	2.1, 20, **111.3**, 14.4	0.261	N/A	≤ 2.9	2.9	42.1
Lead, total	BDL, 5.0, 4.8, **6.7**	0.0021	≤ 500	≤ 5.6	8.5	1.2
Silver, total	BDL, 0.5, **0.9**, 0.5	0.0028	N/A	≤ 0.05	N/A	19.0
Miami-Dade North						
Arsenic, total	**0.83**, BDL, <10.0[c]	1.77	N/A	≤ 50	36	N/A
Copper, total	**19.0**, 16.0, <10.0[c]	0.261	N/A	≤ 2.9	2.9	7.1
Lead, total	**20.2**, BDL, <5.0[c]	0.0021	≤ 500	≤ 5.6	8.5	3.6
Cyanide	**8.41**, 8.0, <4.0[c]	N/A	N/A	≤ 1	1	8.41
Miami-Dade Central						
Copper, total	**35**, 10	0.261	N/A	≤ 2.9	2.9	13.2
Lead, total	**40**, BDL	0.0021	≤ 500	≤ 5.6	8.5	7.2
Silver, total	**14**[d], BDL	0.0028	N/A	≤ 0.05	N/A	296.6
Cyanide	9.6, BDL	N/A	N/A	≤ 1	1	9.6

Note: Data are from Hazen and Sawyer, 1994, unless indicated otherwise by superscripts.

[a] From Bruland, 1983.

[b] Values shown in boldface represent the highest sample values. The dilutions to meet most stringent criteria are calculated in this report based on these highest sample values.

[c] Miami-Dade North District, 1999. See Appendix Table 1-2.

[d] Questionable value, according to Hazen and Sawyer, 1994.

BDL Below detection limits.

N/A Not available.

Note that with the possible exception of silver at the Miami-Dade Central plant (where the value may be incorrect), the dilution required to meet the most stringent water quality standard varies from 1.2 to 42, depending on the metal and the effluent concentration. The 400 m to 800 m mixing zones required under the Florida regulations are intended to provide dilutions ranging from 60:1 to 90:1 or more, based on modeling of the effluent plume. Also, the concentrations of metals in effluent are measured in the parts per billion range, which is low for industrial effluent.

Both the regulatory criteria for Class III marine water and the effluent studies of South Florida ocean outfalls address total metals concentrations rather than dissolved metals. Since dissolved metals are the most bioavailable, they have the most potential to cause ecosystem toxicity effects. Therefore, the values in Table 6-10 can only be used for a general estimate of risks.

The SEFLOE studies did not specifically report on biota in the vicinity of the outfalls, although Hazen and Sawyer (1994) report that a healthy ecosystem appeared to be present. Thus, there is no information concerning potential effects of metals or other stressors on benthic populations of organisms in the outfall areas.

It is therefore not possible to answer the third question concerning evidence of adverse effects of priority pollutants on marine ecosystems in the area, but it is also not possible to rule out adverse effects. No long-term ecological monitoring studies of possible ecological effects were done following the conclusion of the SEFLOE studies in 1994.

Volatile Organic Compounds

Monitoring data were very limited for volatile organic compounds (VOCs); the only detected compound originates from the Miami-Dade Water Sewer North District, which reported a one-time measurement of tetrachloroethene of 4.66 ug/L on March 19, 1999. The Florida Class III marine water-quality standard for tetrachloroethene is ≤8.85 ug/L on an annual average. Although the SEFLOE report sampled for 126 EPA priority pollutants, including tetrachloroethene and many other organic compounds, there were no other reported detections of tetrachloroethene.

The one data point for VOC concentration in effluent is less than the regulatory standard for VOCs in Class III marine waters, and it is less than the reported literature toxicity values (see Section II). VOCs are highly volatile and would be expected to volatilize as the effluent rises to the upper ocean layer. There is little or no evidence concerning VOCs in ecological receptors. Unfortunately, there are not enough data available to offer firm conclusions on this point. Again, while the effluent toxicity testing suggests that there is no short-term acute toxicity, there are no long-term ecological monitoring studies to examine long-term or cumulative ecological changes that might occur as a result of the discharge of effluent containing trace amounts of VOCs. Thus, for VOCs, the small amount of data available from the SEFLOE report suggests that the amounts of VOCs present in treated discharged effluent are very low and becomes even lower when rapid dilution by currents occurs. The toxicity testing indicates no toxic effects for chronic short-term testing or acute toxicity testing.

Synthetic Organic Compounds

Very little data were available concerning linear alkylbenzenesulfonates (a detergent component used as a representative detergent compound in this study) in Florida wastewater effluent. Effluent data from the Miami-Dade North District detected a concentration of methylene blue anionic surfactant (MBAS) surfactant of 0.063 mg/L in the effluent prior to discharge (Table 6-11 from Hazen and Sawyer, 1999). This concentration is lower than the regulated Class III standard of ≤0.5 mg/L for detergents. More information on occurrence and levels of surfactants in treated effluent and in receiving waters and their biological effects is needed to adequately evaluate ecological risks posed by this category of compound.

Table 6-11. MBAS Concentrations in Effluent and Calculated Dilution Concentration at 400 m from the Boil

	MBAS in Effluent (mg/L)	**MBAS in Effluent (mg/L), 60:1 Dilution**	**MBAS in Effluent (mg/L), 90:1 Dilution**	**Background Seawater (mg/L)**	**Class III Standard for Detergents (mg/L)**
MBAS surfactant	0.063[1]	0.001	0.0007	0	≤0.5

[1] Data from Miami-Dade Water/Sewer, North District. 1999. Submission #9903001041, pp. 47-52. Screen effluent collected 3/19/99.

No information is available on monitoring of detergents or other synthetic organic compounds in ecological receptors at or near the effluent outfall.

Hormonally Active Agents

Estrogen equivalences were measured from two grab samples at the Gulfgate and Southgate treatment plants in Sarasota, Florida. Both of these plants treat to advanced wastewater treatment levels and discharge to surface-water creeks. The average concentration of estrogen substances in the treated wastewater effluent was 3.253 nanograms per liter (Frederic Bloettscher, Consulting Professional Engineer, personal communication). At this point, this information only indicates that these substances may be present in treated wastewater effluent intended for discharge into surface water. The literature suggests that, while these concentrations may not induce toxic effects in aquatic organisms, more study is needed concerning the concentrations at which endocrine disruption may occur because of biodegradation byproducts.

No information is available concerning concentrations of estrogen-like compounds in ambient seawater at the southeast Florida ocean outfall sites, nor in ecological receptors at or near the ocean outfall sites. Ongoing and future research should provide a better framework for discussing these compounds and evaluating their risks. Having monitoring data for these constituents in effluent would allow risk to be better evaluated.

6.6.2.4 Toxicity Testing of Effluent

One way to address the question of whether there could be adverse effects from effluent is to conduct toxicity testing of effluent using marine organisms. In order to comply with Florida standards, biological toxicity testing of the diluted and undiluted treated effluent was conducted as part of the SEFLOE studies (Commons et al., 1994a, 1994b) and is summarized in the Hazen and Sawyer (1994) report. A total of 1,727 acute bioassay toxicity tests and 109 short-term chronic bioassays were performed, using diluted effluent water from four ocean outfall wastewater treatment plants and effluent plume samples. Acute toxicity was assessed using the mysid shrimp *Mysidopsis bahia* and the estuarine fish *Menidia beryllina*. Short-term chronic toxicity testing was assessed using those organisms, the sea urchin *Arbacia punctulata*, and the macroalga *Champia parvula*. The bioassay results were compared with current velocities to determine initial and farfield dilutions and to calculate actual exposure times. This allowed researchers to determine potential toxicity of the undiluted effluent, initial dilution, and mixing-zone effluent/seawater mixture.

In all ocean bioassay tests, no potential acute toxicity of effluent or diluted effluent was demonstrated. The bioassays are believed to be conservative: during the tests using diluted effluent, organisms are exposed to the effluent longer and at concentrations that greatly exceed actual measured concentrations of effluent constituents in the ocean outfall area (Commons et al., 1994a, 1994b; Hazen and Sawyer, 1994).

While toxicity testing indicates that there are no acute toxic effects to biological organisms, long-term low-dose chronic toxicity testing was not conducted. Toxicity testing also does not address effects of nutrient enrichment on ecological processes of production, organic cycling, or microhabitats where nutrients may remain more concentrated. Ecological processes that are not addressed by toxicity testing include nutrient-stimulated primary production and respiration, production of organic matter for consumers and detrital feeders, decomposition of organic matter, and the effects of these processes on water quality and biological communities.

6.6.3 Final Conceptual Model of Probable Risk for Ocean Outfalls

The SEFLOE studies provide a risk assessment and a prediction that there should not be any adverse effects resulting from ocean discharge of secondary-treated effluent. This prediction is based largely on the rapid dispersal and dilution of the effluent plumes by the Florida Current and that the treated effluent has relatively low concentrations of stressors to begin with. Prevailing current directions and fast current speeds of the Florida Current are major factors that decrease risk for the six ocean outfalls that discharge into the Florida Current. Current speeds can be more than 60 or 70 cm/sec for the Florida Current, while speeds of 20 to 40 cm/sec commonly occur. Northerly flow with the fastest speeds occurs approximately 60% of time. Southerly flow with similar or lesser speeds occurs about 30% of time. Flow in other directions (easterly, westerly) exhibits the lowest current speeds and occurs less than 10% of the time. Westerly flow towards the east coast of Florida, which represents the highest risk, is estimated to occur less than approximately 4% of the time, while easterly flow is estimated to occur less than approximately 6% of the time.

Other factors that decrease risk are the distance of the outfalls from land. The lowest risk outfalls are farthest from land (Miami-Dade Central outfall), while the highest risk outfalls are closest to land (Boca Raton, Del Ray Beach). The use of multiport diffusers, compared to the use of single-port diffusers, appears to aid in dispersal of the effluent plume over a wider area, decreasing potential risk. Discharging the effluent at a faster initial speed also appears to increase the rate of dispersal and dilution of the effluent plume.

Based on toxicity testing of marine organisms, there is no evidence that the diluted effluent causes acute toxic effects or short-term chronic effects.

Based on nitrogen isotope studies of organic matter in sediments and nutrients in the water column, it does not appear that the nitrogen in outfall effluent is taken up in significant amounts by phytoplankton in the area. This may be because of the rapid dilution of the effluent nitrogen by the Florida Current.

The state of Florida requires that Class III water quality standards be met outside a mixing zone of 502,655 m^2 around the outfall. This mixing zone allows for dispersal, mixing, and dilution of the effluent plume. A mixing zone with a circular radius of 400 m measured from the outfall was used by the utilities in the SEFLOE study. This circle would cover an area equivalent to 502,655 m^2. The use of a circular mixing zone is not required by Florida, but is used for ease of defining an area to monitor.

Concentrations of pathogens are controlled at the treatment plant through chlorination to meet water-quality standards within the required mixing zone; viruses and most bacteria are expected to be adequately inactivated by chlorine. However, there is no filtration to remove *Cryptosporidium* and *Giardia*. Lack of treatment to remove pathogenic protozoans probably constitutes the greatest human health risk posed by this wastewater management option.

Pathogenic protozoans may also pose significant ecological risks related to infections of marine mammals. The effects of pathogenic protozoans on aquatic organisms need to be further investigated.

Concentrations of priority pollutant metals in undiluted effluent may exceed marine water-quality standards (but meet effluent standards), but there is no information on actual receptors or exposure pathways because there were no benthic tissue monitoring studies, benthic ecology studies, or studies of trace metals in the water column as part of the SEFLOE studies. The results of the SEFLOE study for metals monitoring indicates that, in general, water-quality standards are met at 400 m or 800 m.

In coastal areas from North Carolina south to Florida, oysters, other shellfish, and sediments have elevated concentrations of arsenic, although not at levels that would pose a threat to humans or to marine life, according to a NOAA National Status and Trends Program report (Valette-Silver et al., 1999). Postulated sources of arsenic include pesticides, mining of arsenic-containing phosphate rocks, atmospheric dust, river and groundwater inputs, and ocean upwelling. The NOAA study did not examine ocean outfalls as potential sources of metals. Since oysters are a nearshore intertidal species, it is most likely that the arsenic is derived from terrestrial and coastal sources close at hand, rather than the ocean outfalls.

Concentrations of priority pollutant organic compounds in treated wastewater are generally very low. Monitoring data were very limited for volatile organic compounds; the only data available originates from the Miami-Dade Water Sewer North District, which reported a one time measurement of tetrachloroethene of 4.66 μg/L, which meets the Florida Class III annual average marine water-quality standard for tetrachloroethene of ≤8.85 μg/L. There were no reported detections of tetrachloroethene in the SEFLOE study.

Concentration of a surfactant, MBAS, of 0.063 mg/L in the effluent is lower than the regulated Class III standard for detergents of ≤0.5 mg/L. The effects of low concentrations of surfactants on aquatic organisms in natural settings are not well understood or documented. The lack of knowledge concerning effects of surfactants on the tissues and physiologic functions of aquatic organisms is not cause to eliminate this as a potential stressor. Surfactants act to decrease surface tension and reduce adhesion, which may affect microorganisms or for other functions in higher organisms.

Despite the lack of information on effects of endocrine disruptors in South Florida marine waters, effluent discharged to marine waters typically contains such compounds. Endocrine disruptors may pose a concern because they can cause effects in aquatic organisms at very low concentrations and because they are typically present in wastewater and not removed by existing wastewater treatment technology. However, better information on the concentrations of these substances in Florida wastewater, coastal waters, and in aquatic organisms is needed. A better understanding of their effects is also needed.

In summary, the chlorinated discharged effluent largely meets Class III water-quality standards for all regulated wastewater constituents within 400 m of the outfalls, with exceptions as noted.

The lack of long-term ecological, microbial pathogen, and chemical monitoring studies makes it difficult to evaluate whether the conclusions of the SEFLOE studies will continue to hold true in the future. It is not possible to evaluate whether long-term, cumulative, chronic risks exist or not. There are no ongoing monitoring studies downcurrent of any of the effluent plumes or within the footprint of the effluent plume. An initial project to formulate a long-term study to address issues concerning nutrients, growth of nuisance macroalgae (*Codium*), productivity, and the benthic community had begun in the early 1990s, but this project did not go forward at that time. A long-term extensive program is now being contemplated that will examine long-term monitoring of the outfalls and adjacent areas and examine sources of nutrient loading (personal communication, John Proni).

Potential long-term ecological risks may exist, particularly within the 400-m mixing zone, but also outside it. Nutrients, including both nitrogen and phosphorus, may constitute the most important ecological stressors resulting from ocean outfalls. Nutrient dispersal poses concerns because coastal water quality throughout Florida is already impacted by a variety of human activities on land, such as agriculture, septic systems, urbanization, and channelization of wetlands. The cumulative ecological risks associated with continually discharging nutrients into the Florida Current, and ultimately the Gulf Stream, are not known. The same is true of other effluent constituents, such as metals and organic compounds.

Information needed to assess whether or not there is a long-term, chronic, or cumulative adverse effect on marine organisms would include the following:

- Monitoring of benthic communities in the plume track and adjacent areas
- Tissue studies of bioaccumulation in the food chain
- Monitoring of primary production and nutrient uptake and cycling
- Tracer studies of the sources of nitrogen and phosphorus being utilized by phytoplankton
- Marine particle fluxes of metals in the plume track and adjacent areas to determine whether metals discharged in the effluent adsorb onto marine snow particles or precipitate as solid particles or not
- Related studies of the ecology and chemistry of the ocean within the plume footprint and adjacent to it.

Human health risks are of some concern, both within the 400-m mixing zone and outside of it, primarily because treatment of effluent prior to discharge via ocean outfalls does not include filtration to remove *Cryptosporidium* and *Giardia*. The most probable human exposure pathways include fishermen, swimmers, and boaters who venture out into the Florida Current and experience direct contact, accidental ingestion of water, or ingest fish or shellfish exposed to effluent. Otherwise, there is a very small, but not nonzero, chance for onshore or nearshore recreational or occupational users to be exposed to effluent constituents, since there is a small (10%) chance that currents will change direction to east or west.

Finally, there is the question of whether any adverse effects, if they exist, are reversible. Monitoring studies of Tampa Bay, where tertiary treatment of effluent is now required instead of secondary treatment (see Chapter 7, Surface Water Discharge) indicates that water quality and benthic ecological conditions will improve upon upgrading treatment (Lipp et al., 2001). Even at highly affected marine disposal sites where sewage sludge has been disposed of, cessation of disposal has resulted in improvement of the benthic communities and water and sediment quality (Studholme et al., 1995, 1989). Because the existing southeast Florida ocean outfalls discharge to the Florida Current, recovery from any adverse effects, if they exist, would probably be rapid because of the rapid flushing by the Florida Current.

6.7 Potential Effects of Data Gaps

Because of the relatively short term of the SEFLOE studies (several years), the long term or cumulative ecological risks of nutrient loading and loading of other effluent constituents cannot be evaluated. Some of the specific questions that cannot be answered at this time include:

- Effects of adding nitrogen and phosphorus to the Gulf Stream nutrient budget and its potential to affect primary productivity in the open ocean
- Effects on productivity and marine organisms within the plume where nutrient concentrations are higher than background concentrations
- Potential changes in the ratio of nitrogen to phosphorus and effects on phytoplankton diversity
- Frequency of harmful algal blooms in the vicinity of the outfalls
- Bioaccumulation of effluent constituents by marine organisms in the vicinity of the outfall and its plume footprint
- Changes in trophic structure and potential food-web effects
- Effect of global climate change or other factors on the Florida Current that would cause changes in current speed, direction, or position and affect dilution of the effluent plume, affecting risk
- Long-term, chronic effects of exposure of benthic or nektonic marine organisms to effluent constituents in the vicinity of the effluent plume.

Regarding potential human health risk issues, there are also significant data gaps. Some examples of questions that remain unanswered include the following:

- Are *Cryptosporidium* and *Giardia* present in nearshore waters that are used by humans, are their concentrations within safe limits, and if not, can their sources be determined (for example, onshore sources versus ocean outfalls)?
- Are pathogenic *E. coli*, enteric viruses, and other enteric pathogens present in the treated effluent in numbers high enough to be of concern for human health?
- What is the relative contribution of enteric pathogens and other stressors from existing onsite septic disposal systems and other sources versus ocean outfalls to water quality near the outfalls?

These are just a few of the issues that remain to be addressed if long-term risk from ocean outfalls is to be fully assessed.

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