Initial Dilution of Southeast Florida Ocean Outfalls

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Abstract: Initial dilutions of four ocean outfalls (the Miami-Central, Miami-North, Hollywood, and Broward outfalls) on the east coast of South Florida were determined from dye and salinity studies. In the dye studies, continuous injections of the red dye Rhodamine-WT into effluent were conducted; dye concentrations were measured using a deck-mounted fluorometer with a ship-towed sampler and from grab water samples. In the salinity studies, temperature and conductivity were measured using a towed conductivity-temperature-depth device (CTD); salinity deficit was taken as a tracer to determine initial dilution. Results show that initial dilutions determined from both methods are consistent. Data for initial dilution and for environmental and effluent parameters are interpreted using the dimensional analysis method. A comparison is made between the present data and data from previous studies. Data for Hollywood and Broward outfalls (single-port discharges) are consistent with previous data. Data for Miami-Central and Miami-North outfalls (multiport diffuser discharges) are not consistent with data for single-port discharges. A value of $C_1 = 0.15$ for the asymptotic solution for the buoyancy-dominated nearfield is suggested.

Introduction

Initial dilution is one of the most important characteristics in outfall design and environmental-impact assessment of effluent discharges. Subsequently, many studies on initial dilution have been performed in past decades. Although fundamental theories on the initial mixing of outfall plumes have been established [e.g., Wright (1977); Fischer et al. (1979); Roberts (1979); Roberts et al. (1989a), (1989b), and (1989c)], these theories were mainly compared with laboratory experiments, and the verification of the theories with field data is still rare.

This paper presents field data and analysis for initial dilutions of four ocean outfalls (the Miami-Central, Miami-North, Hollywood, and Broward outfalls) located on the east coast of South Florida. Dilutions were determined from dye and salinity studies that were part of a project called Southeast Florida Outfalls Experiment II (SEFLOE II). It is noted that in the present paper, "initial dilution" refers to the minimum surface or near-surface dilution. All four outfall plumes surface, resulting in so-called "boils,"

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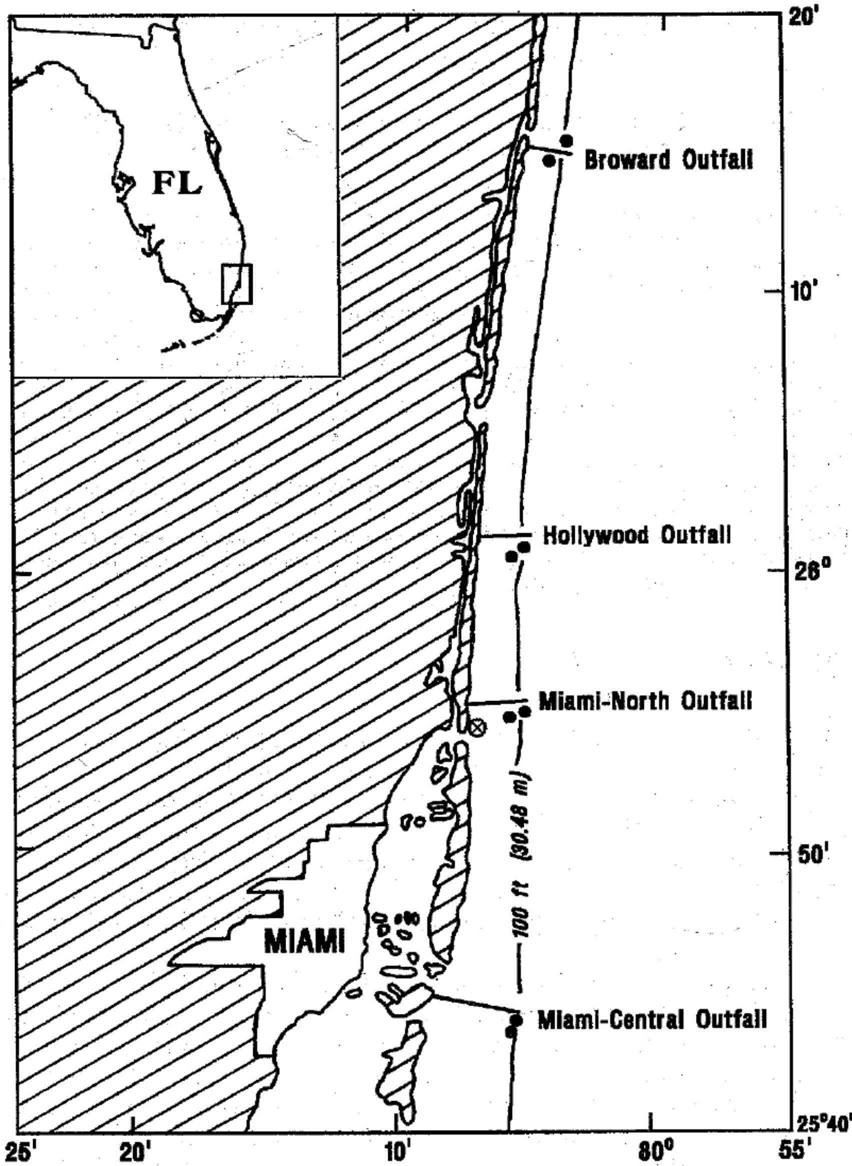

FIG. 1. Location of Four Ocean Outfalls on East Coast of South Florida (● Current Meter Station; ⊗ Tide Gauge Station)

throughout the course of a year. In general, the surface or near-surface dilution is the dilution measured within outfall boils.

Fig. 1 shows the locations of four ocean outfalls investigated in the SEFLOE II project. All four outfall sites are located in the western boundary region of one of the world's most powerful currents, the Gulf Stream or Florida Current. These outfalls discharge secondary-treated domestic sewage whose density is approximately 0.998 g/cm^3. Two of these outfalls, Miami-Central and Miami-North, have multiport diffusers; the other two, Hollywood and Broward, have only single-port outlets. The water depth at diffusers or outlets of these outfalls ranges from 28 to 34 m. Table 1 summarizes the characteristics of these outfalls.

TABLE 1. Characteristics of SEFLOE II Outfalls

Parameter (1)	Miami-Central (2)	Miami-North (3)	Hollywood (4)	Broward (5)
Average discharge (m^3/s)	5.26	3.88	1.32	1.90
Discharge depth (m)	28.2	29.0	27.0	32.5
Distance off shore (m)	5,730	3,350	3,050	2,130
Diffuser length (m)	39	110	0	0
Number of ports	5	12[a]	1	1
Spacing of ports (m)	9.8	12.2	0	0
Diameter of ports (m)	1.22	0.61	1.52	1.37
Port orientation	vertical	horizontal	horizontal	horizontal

[a]There are two opposed ports at the ends of the diffuser.

DYE STUDIES

Dye measurements at all four outfalls to investigate initial dilution and plume dispersion were made during two cruise periods, September 18–25, 1991 and February 3–12, 1992. These cruise periods are referred to as intensive-measurement cruise periods. The research vessel used in the investigations was a 103-ft-long (31.4 m) ship named *Coral Reef II*. This ship was equipped with both GPS and LORAN systems for navigation and sampling station positioning.

During each cruise, measurements at an outfall usually lasted about 10–24 h. Two or 3 h prior to and during this period, red dye (Rhodamine-WT) liquid was continually injected into effluent at the treatment plant. Effluent dye concentration within the treatment plant was measured continuously using a fluorometer. Since effluent flow rate varied with time, the dye injection rate was adjusted in accordance with real-time fluorometer readings to keep the dye concentrations of effluent as constant as possible.

Dye concentrations at outfall boils were determined using two sampling methods. The first was direct and continuous measurement by a deck-mounted fluorometer whose underway sampler was towed and kept at approximately 2 m beneath the water surface. The time interval for the fluorometer measurements was 1 s. The second method was water-bottle sampling; when the ship crossed a boil, grab water samples were taken from the water surface using sampling bottles. Dye concentrations of these samples were later measured using a fluorometer. A towed acoustical system and methodology were utilized for guidance of grab sampling. This technique has been discussed by Dammann et al. (1991).

The highest dye concentration extracted from continuous sampling and grab-sampling measurements during a crossing of a boil was used to estimate the initial dilution

$$D_m = \frac{C_o}{C_m} \tag{1}$$

where D_m = minimum surface or near-surface dilution; C_o = dye concentration in effluent; and C_m = maximum dye concentration in the boil. In general, dye concentrations measured by the towed fluorometer simultaneous with the grab samples were lower than those measured from the grab samples. This difference occurs because grab samples were collected at the water surface while the towed fluorometer measured dye concentrations at a level of about 2 m beneath the water surface. Also, before the dye concentration of a water sample was measured by the fluorometer, it traversed a 30-m hose and had been mixed further. Therefore, only eight among a total of 47 C_m values were taken from the towed fluorometer data, and the rest were taken from the grab sample data. Additionally, C_m values from the fluorometer measurements were peaks extracted from records without time-averaging.

In addition to dye measurements, currents were measured with mooring systems deployed in the vicinities of each outfall outlet (or diffuser). Each mooring system consisted of two Aanderaa current meters, with one of them located close to the middle depth of the water. CTDs were used to measure temperature and conductivity profiles, from which density profiles can be generated.

SALINITY STUDIES

In addition to the intensive cruises, small-boat tests were made once or twice a month from August 1991 through August 1992. Two small boats equipped with LORAN systems were used. One was a 26.5-ft-long (8.1 m) boat named *Hazen and Sawyer*; the other was a 28-ft-long (8.5 m) boat named *Park Sounder*.

During each field exercise, a boat towed a CTD through a boil and plume at 1 m or less beneath the water surface, the time interval of sampling was 2–2.5 s. The CTD was also used to measure temperature and conductivity profiles before and after a towing operation. Current mooring systems were deployed in some periods that covered test durations.

The variation of salinity along tracks were generated from the towed CTD data. The lowest salinity value was extracted from the records during boil crossings and was used to calculate the initial dilution as follows:

$$D_m = \frac{S_{ac} - S_e}{S_{ac} - S_m} = \frac{\Delta S_e}{\Delta S_m} \tag{2}$$

where S_{ac} = characteristic ambient salinity; S_m = minimum salinity in a boil (S_m is an instantaneous salinity value and no averaging over time is made); S_e = effluent salinity; ΔS_m = maximum salinity deficit in a boil; and ΔS_e = salinity deficit in effluent.

In (2) salinity deficit is taken as a tracer in the determination of initial dilution. Eq. (2) is exact for a uniform ambient salinity profile, but is only an approximation if salinity is stratified. If we assume that salinity varies linearly from the water surface to the bottom, based on the conservation of salinity and the concept of entrainment, the characteristic salinity may be estimated as

$$S_{ac} = \frac{5}{8} S_{as} + \frac{3}{8} S_{ab}; \qquad \text{for BDNF} \tag{3}$$

$$S_{ac} = \frac{2}{3} S_{as} + \frac{1}{3} S_{ab}; \qquad \text{for BDFF} \tag{4}$$

where S_{as} and S_{ab} = salinities at the water surface and bottom, respectively; BDNF stands for buoyancy-dominated nearfield; and BDFF stands for buoyancy-dominated farfield. The definitions of BDNF and BDFF will be given later. The derivation of (3) and (4) is shown in Appendix I.

RESULTS

During the SEFLOE II project, about 100 initial-dilution data were obtained from both dye and salinity studies for the four ocean outfalls. Tables 2–5 show a total of 72 initial dilution data (47 from the dye study and 25 from the salinity study) with corresponding parameters, including: Q, the total effluent discharge rate; u, the ambient current speed measured at a depth; u_a, the depth-averaged current speed; ρ_{ao}, the depth-averaged density; N, the buoyancy frequency [$N = (-g/\rho_{ao}\, d\rho_a/dz)^{1/2}$, where g = gravitational acceleration, assuming density was linearly stratified]; θ, the current direction; l_b and l_m, the length scales for single-port discharges; and the ratio of l_b and l_m ($l_b = B/u_a^3$, where B = buoyancy flux defined by $B = Q_s g'_o$; g'_o = reduced gravitational acceleration defined by $g'_o = (\rho_{ao} - \rho_o)g/\rho_{ao}$; ρ_o = density of the effluent; and Q_s = effluent flow rate from a single port; and $l_m = M^{1/2}/u_a$, where $M = Q_s u_j$, and u_j = exiting velocity of the single-port discharge). The dilution data without these corresponding parameters cannot be used for the correlation analysis and are not shown in these tables.

Fig. 2 shows typical density profiles measured in the vicinity of the Miami-Central outfall. Density profiles measured in other outfall areas are similar to those shown in Fig. 2. It is seen in Fig. 2 that density profile varies from season to season; uniform profiles are found during winter months and nearly linear stratifications are observed during summer months.

Fig. 3 shows typical current-speed profiles measured at a site near the Miami-Central outfall by an acoustic Doppler current profiler (ADCP). This ADCP was installed for the period from July 11 to August 10, 1992. It should be noted that current speeds measured near the water surface may not be accurate, because the water surface could contaminate the measurements. The manufacturer (RD Instruments) recommends not using measurements acquired beyond 85% of the range when surface or bottom reflections are present (Appell et al. 1991). In our case, where water surface reflections are present the 15% of the range of the ADCP measurements is about 4 m from the surface. The current-speed profile is not uniform and the relative variation of speeds near the water surface and speeds near the bottom can be as much as 300%. The ADCP data can be used to obtain the depth-averaged current speed and to establish the relationships between the depth-averaged speed and speeds at other depths (Proni et al. 1994).

We have mentioned that the "initial dilution" measured is actually the minimum surface or near-surface dilution. During all field sampling cruises, surfacing plumes were observed, even in the summer months when the water column density stratification was present. This was because the initial dilutions of these outfalls were low enough and the density stratifications were weak enough to allow the surfacing of plumes. However, for the Miami-North outfall, some trapping of portions of rising plumes may have occurred.

Some uncertainties or errors may be contained in the data. During dye tests, the chief concern in gathering water bottle samples is, of course, ascertaining that the samples are indeed gathered at a maximum concentration point within the boil. The appearance of a surface boil permitted visual observation of the plume, thereby assisting in sample bottle placement. This advantage was not present at night, and, in fact, nocturnal samples might yield lower measured dye concentrations, indicating greater dilution than did samples gathered in daylight at nearly the same conditions. (It is assumed that the higher nocturnal dilutions observed resulted from less accurate targeting of the boil in sampling, rather than from any potential

TABLE 2. Summary of Field Test Parameters for Miami-Central Outfall

Number (1)	Date (2)	Time (3)	D_m (4)	Q (m³/s) (5)	u (cm/s) (6)	u_a (cm/s) (7)	l_b (m) (8)	l_m (m) (9)	l_b/l_m (10)	ρ_{ao} (g/cm³) (11)	N (10^{-3} s^{-1}) (12)	θ (degrees) (13)
1	12/04/91	13:20	24.4	5.97	12.7	14.3	104.3	7.7	13.5	1.0241	0.0	0
2	01/21/92	12:20	20.9	6.42	18.3	19.4	46.0	6.1	7.5	1.0249	0.0	180
3	05/05/92	11:00	29.3	5.70	15.1	16.4	66.7	6.4	10.4	1.0245	6.4	180
4	05/21/92	11:30	44.7	5.04	27.3	28.1	11.5	3.3	3.5	1.0240	4.4	0
5	06/03/92	11:30	13.7	6.81	4.5	7.2	921.9	17.5	52.7	1.0239	4.7	70
6	06/18/92	11:20	42.0	6.44	50.0	52.5	2.2	2.3	1.0	1.0233	8.2	0
7	07/07/92	12:00	18.6	6.29	30.0	30.8	11.0	3.8	2.9	1.0243	13.1	0
8	07/28/92	11:00	18.1	6.32	4.0	6.8	972.5	17.2	56.5	1.0227	10.0	90
9	02/07/92	10:13	30.0	6.21	15.3	16.6	68.8	6.9	10.0	1.0248	0.0	180
10	02/07/92	11:11	25.8	6.52	17.6	18.7	50.6	6.5	7.8	1.0248	0.0	180
11	02/07/92	13:55	39.3	6.92	17.6	18.7	53.7	6.8	7.8	1.0248	0.0	135
12	02/07/92	14:55	15.5	6.61	17.8	18.9	49.7	6.5	7.7	1.0248	0.0	90
13	02/07/92	18:08	19.0	6.19	20.0	21.0	34.0	5.5	6.2	1.0248	0.0	315
14	02/07/92	19:17	24.7	6.05	19.0	20.0	38.3	5.6	6.9	1.0248	0.0	330
15	02/07/92	22:59	20.0	6.10	19.5	20.5	36.0	5.5	6.5	1.0248	0.0	0
16	02/07/92	23:55	29.7	6.05	20.0	21.0	33.1	5.3	6.2	1.0248	0.0	0
17	02/08/92	03:01	29.7	4.53	17.6	18.7	35.2	4.5	7.8	1.0248	0.0	15
18	02/08/92	04:37	43.1	4.68	14.1	15.5	63.3	5.5	11.4	1.0248	0.0	0
19	02/08/92	07:18	25.3	4.64	12.9	14.5	77.3	5.9	13.0	1.0248	0.0	0
20	02/08/92	08:40	19.0	5.69	11.8	13.5	117.4	7.8	15.0	1.0248	0.0	345

Note: No. 1–8 are from salinity studies; No. 9–20 are from dye studies; and currents were measured at a depth of 16.8 m.

TABLE 3. Summary of Field Test Parameters for Miami-North Outfall

Number (1)	Date (2)	Time (3)	D_m (4)	Q (m³/s) (5)	u (cm/s) (6)	u_a (cm/s) (7)	l_b (m) (8)	l_m (m) (9)	l_b/l_m (10)	ρ_{ao} (g/cm³) (11)	N (10^{-3} s^{-1}) (12)	θ (degrees) (13)
1	09/04/91	12:40	51.7	4.47	56.5	44.7	1.2	2.3	0.5	1.0216	8.4	0
2	09/06/91	11:10	31.1	4.31	26.0	23.5	7.6	4.1	1.8	1.0214	5.1	180
3	01/15/92	13:50	49.1	3.90	12.0	12.6	50.6	7.0	7.2	1.0247	2.2	0
4	05/27/92	11:56	47.7	3.80	10.4	12.3	51.8	7.0	7.4	1.0239	3.6	0
5	09/18/91	10:52	49.3	5.03	15.3	15.7	30.6	7.2	4.2	1.0220	7.0	15
6	09/18/91	11:31	44.1	5.06	15.6	15.9	29.7	7.2	4.1	1.0220	7.0	15
7	09/18/91	16:15	22.9	4.83	4.7	7.7	248.0	14.1	17.6	1.0220	7.0	15
8	09/18/91	16:59	19.0	4.91	4.7	7.7	252.5	14.4	17.6	1.0220	7.0	128
9	09/18/91	20:34	27.5	5.16	5.5	8.3	212.4	14.1	15.1	1.0220	7.0	90
10	09/18/91	21:30	28.0	4.89	8.5	10.6	96.8	10.4	9.3	1.0220	7.0	15
11	09/19/91	01:34	27.5	3.82	7.3	9.7	98.1	8.9	11.1	1.0220	7.0	315
12	09/19/91	02:21	32.8	3.31	7.3	9.7	85.7	7.7	11.1	1.0220	7.0	270
13	02/03/92	11:39	54.6	4.56	11.8	12.5	60.7	8.2	7.4	1.0247	0.0	300
14	02/03/92	13:15	54.6	3.88	10.8	11.7	63.3	7.5	8.4	1.0247	0.0	0
15	02/03/92	15:17	49.7	3.94	9.6	10.8	81.4	8.2	9.9	1.0247	0.0	330
16	02/03/92	16:49	46.7	3.94	10.2	11.3	71.1	7.9	9.0	1.0247	0.0	330
17	02/03/92	19:28	72.0	4.25	9.4	10.7	90.3	9.0	10.1	1.0247	0.0	290
18	02/03/92	21:51	60.0	3.99	8.2	9.8	110.2	9.2	12.0	1.0247	0.0	290
19	02/04/92	01:42	65.5	2.83	9.4	10.7	60.5	6.0	10.1	1.0247	0.0	0
20	02/04/92	03:08	72.0	2.33	9.4	10.7	49.3	4.9	10.1	1.0247	0.0	0
21	02/04/92	05:24	65.5	2.50	9.4	10.7	53.0	5.3	10.1	1.0247	0.0	345
22	02/04/92	08:19	31.7	4.50	7.1	8.9	166.5	11.4	14.6	1.0247	0.0	315
23	02/04/92	09:55	47.5	4.29	8.2	9.8	118.7	9.9	12.0	1.0247	0.0	260

Note: No. 1–4 are from salinity studies; No. 5–23 are from dye studies. Currents were measured at a depth of 6.5 m for No. 1, 2, and 5–12; 13.6 m for No. 3, and 13–23; and 17.1 m for No. 4.

TABLE 4. Summary of Field Test Parameters for Hollywood Outfall

Number (1)	Date (2)	Time (3)	D_m (4)	Q (m³/s) (5)	u (cm/s) (6)	u_a (cm/s) (7)	l_b (m) (8)	l_m (m) (9)	l_b/l_m (10)	ρ_{ao} (g/cm³) (11)	N (10^{-3} s^{-1}) (12)	θ (degrees) (13)
1	11/07/91	10:40	24.5	1.71	27.1	24.6	28.5	5.1	5.5	1.0235	0.0	180
2	12/10/91	10:20	27.2	1.53	30.0	27.0	20.0	4.2	4.8	1.0243	2.5	190
3	12/12/91	10:30	45.2	1.36	45.0	40.1	5.4	2.5	2.2	1.0243	1.8	180
4	01/29/92	10:40	15.1	1.45	6.0	8.5	619.1	12.6	49.2	1.0250	0.0	315
5	06/02/92	09:45	16.7	1.36	8.0	10.2	318.7	9.9	32.3	1.0235	—	190
6	06/09/92	10:10	15.9	1.05	7.5	9.8	281.3	7.9	35.4	1.0238	8.6	270
7	07/09/92	09:40	31.4	1.75	23.8	24.6	28.6	5.3	5.4	1.0229	—	10
8	09/24/91	11:37	36.5	1.93	25.9	23.4	37.0	6.1	6.1	1.0235	10.0	350
9	09/24/91	18:07	31.6	1.66	37.1	31.4	13.2	3.9	3.4	1.0235	10.0	0
10	02/09/92	11:34	35.2	1.42	15.3	16.6	79.0	6.4	12.4	1.0250	0.0	180
11	02/09/92	13:02	26.2	1.47	18.8	19.9	47.2	5.5	8.7	1.0250	0.0	180
12	02/09/92	16:25	19.3	1.42	13.5	15.0	107.0	7.0	15.2	1.0250	0.0	180
13	02/09/92	19:43	30.1	1.45	12.9	14.5	120.3	7.4	16.3	1.0250	0.0	180
14	02/09/92	21:08	36.7	1.40	14.1	15.5	95.5	6.7	14.3	1.0250	0.0	190
15	02/09/92	23:56	54.8	1.31	16.5	17.7	60.1	5.5	10.9	1.0250	0.0	190
16	02/10/92	03:11	63.3	1.14	15.3	16.6	63.2	5.1	12.4	1.0250	0.0	190
17	02/10/92	04:14	67.8	0.96	16.5	17.7	44.1	4.0	10.9	1.0250	0.0	180
18	02/10/92	05:59	63.0	0.88	16.5	17.7	40.1	3.7	10.9	1.0250	0.0	180
19	02/10/92	06:54	55.0	1.15	16.5	17.7	52.5	4.8	10.9	1.0250	0.0	180

Note: No. 1–7 are from salinity studies; No. 8–19 are from dye studies. Currents were measured at a depth of 13.2 m for No. 1–3; 6.5 m for No. 8 and 9; and 16.5 m for the rest.

TABLE 5. Summary of Field Test Parameters for Broward Outfall

Number (1)	Date (2)	Time (3)	D_m (4)	Q (m³/s) (5)	u (cm/s) (6)	u_a (cm/s) (7)	l_b (m) (8)	l_m (m) (9)	l_b/l_m (10)	ρ_{ao} (g/cm³) (11)	N (10^{-3} s^{-1}) (12)	θ (degrees) (13)
1	12/09/91	11:30	56.8	1.84	33.6	34.5	11.5	4.4	2.6	1.0243	0.0	0
2	01/22/92	12:00	33.0	1.63	16.5	16.1	101.8	8.3	12.3	1.0248	0.0	0
3	01/30/92	11:56	14.8	2.12	7.1	8.9	784.9	19.6	40.1	1.0248	0.0	180
4	03/24/92	11:50	31.0	1.46	7.1	9.4	464.4	12.8	36.4	1.0251	12.4	15
5	04/13/92	12:20	25.0	1.87	5.9	8.4	817.3	18.4	44.5	1.0245	10.6	0
6	04/22/92	10:45	22.5	1.61	15.3	16.6	92.4	8.0	11.6	1.0249	16.1	15
7	02/11/92	18:39	84.0	2.06	24.7	25.5	32.7	6.6	4.9	1.0250	0.0	180
8	02/12/92	00:16	67.8	1.83	24.7	25.5	29.0	5.9	4.9	1.0250	0.0	180
9	02/12/92	06:59	32.0	2.05	12.9	14.5	176.9	11.6	15.2	1.0250	0.0	180
10	02/12/92	11:29	58.9	1.52	9.4	11.4	270.6	11.0	24.6	1.0250	0.0	135

Note: No. 1–6 are from salinity studies; No. 7–10 are from dye studies. Currents were measured at a depth of 13.7 m for No. 2 and 3; and 17.1 m for the rest.

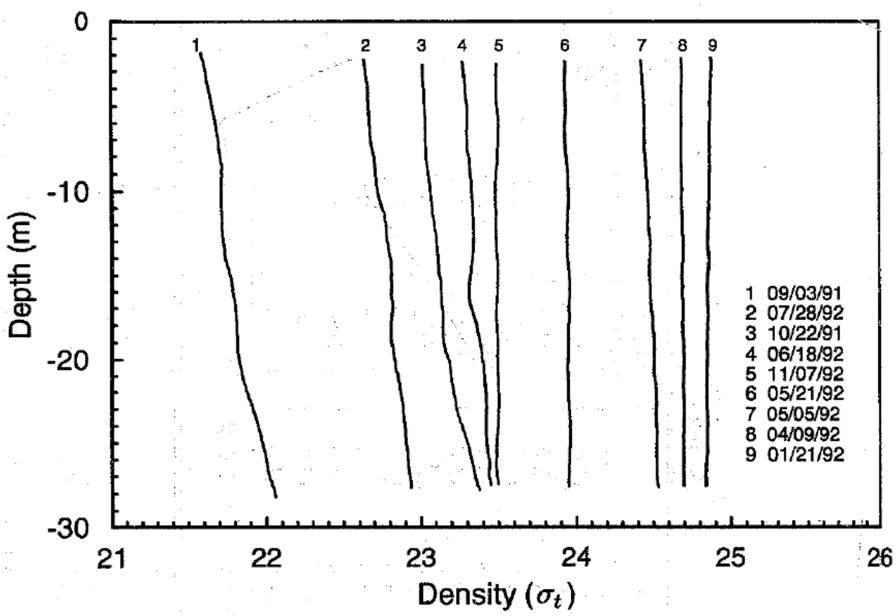

FIG. 2. Typical Density Profiles at the Miami-Central Outfall

unknown nocturnal dilution effect). This can be seen by a comparison of the nocturnal dye concentration determined dilutions in the data numbers 15–19 and the dye concentration determined dilutions gathered in daylight in the data numbers 10–14 at the Hollywood outfall (Table 4). On the other hand, all salinity measurements were made during the day, and there is good agreement between dye concentration determined dilutions gathered during the day and salinity determined dilutions.

The data shown in Tables 2–5 can be analyzed using a framework of dimensional analysis. This analysis is well known [e.g., Lee and Neville-Jones (1987)], and the resulting functional form for dilution is

$$\frac{D_m Q_s}{u_a l_b^2} = f\left(\frac{H}{l_b}\right) \tag{5}$$

where u_a = characteristic speed of the ambient current; and H = water depth above discharge. In deducing (5), one has to make two assumptions: (1) that the discharge is buoyancy-dominated, which means that $l_b/l_m >> 1$; and (2) that the ambient density stratification is relatively weak so that a surface plume will be present. This is the case for these outfalls throughout a year.

In two limits, buoyancy-dominated near field (BDNF) and buoyancy-dominated far field (BDFF), asymptotic solutions for initial dilution can be written as [e.g., Lee and Neville-Jones (1987)]

$$\frac{D_m Q_s}{u_a l_b^2} = C_1 \left(\frac{H}{l_b}\right)^{5/3}; \qquad \text{for BDNF} \tag{6}$$

$$\frac{D_m Q_s}{u_a l_b^2} = C_2 \left(\frac{H}{l_b}\right)^{2}; \qquad \text{for BDFF} \tag{7}$$

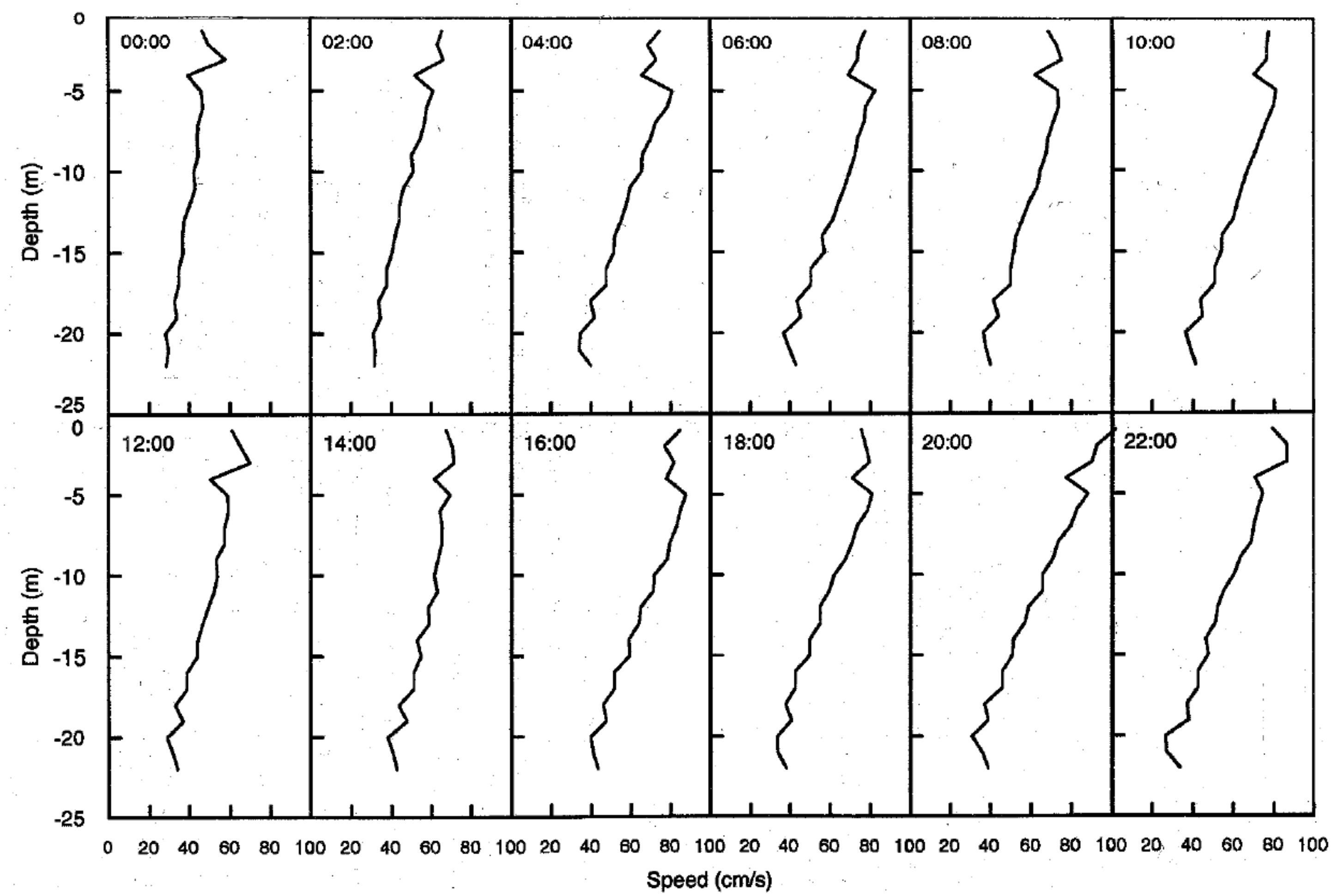

FIG. 3. Typical Current-Speed Profiles from the ADCP Measurements at the Miami-Central Outfall (7/12/92)

where BDNF = region where $H/l_b << 1$; and BDFF = region where $H/l_b >> 1$. A transition between these two regions is expected at $H/l_b = 1$ (Lee and Cheung 1991; Wood 1993). Lee & Neville-Jones (1987) used (6) and (7) to interpret field data at a number of United Kingdom outfalls, and determined $C_1 = 0.31$ and $C_2 = 0.32$.

To present our data shown in Tables 2–5 in the form of (5), we need to make the following assumptions.

1. Eq. (5) also applies to the diffuser discharges of the Miami-Central and Miami-North outfalls, and Q_s is taken to be the flow rate of one port. Lee (1986) suggested that, if the ratio of the port spacing to the discharge depth is greater than 1/3, diffuser discharges could be considered equivalent to single-port discharges. In our case, this ratio is 1/2.9 for the Miami-Central outfall diffuser and 1/2.4 for the Miami-North outfall diffuser. Also, during field tests, multiple boils were observed at these outfalls; it seems that partial rather than full merging occurred at the water surface. This assumption is an approximation, but it makes the analysis simple.
2. The depth-averaged current speed (i.e., u_a shown in Tables 2–5) is taken as the characteristic current speed. u_a is estimated from relationships between the depth-averaged current speed and the current speeds at other depths, established from the ADCP data mentioned earlier. All four outfall sites are located in the same geophysical region, with similar current patterns and nearly the same water depth. Therefore the relationships are assumed to apply to all four outfalls, though the ADCP was deployed at a site near the Miami-Central outfall.
3. Depth-averaged density (i.e., ρ_{ao} shown in Tables 2–5) is taken as a characteristic ambient density.
4. The water depth H above discharge for each outfall is taken to be a constant, as shown in Table 1. Tide height data for the years of 1991 and 1992 have been analyzed. Results show that the standard deviation for the tide height is 0.3 m, twice of which is only about 2% of the water depths above discharges for these outfalls. Therefore, the variation of discharge depth due to tides is negligible.

Following the previous assumptions, quantities in (5) are calculated and then plotted in Fig. 4. The shaded area in the figure represents the data from previous studies, as summarized by Lee and Neville-Jones (1987) and Wood (1993). The solid line is the BDNF solution with $C_1 = 0.31$ and the dot-dashed line is the BDFF solution with $C_2 = 0.32$, given by Lee and Neville-Jones (1987). The dashed line is the BDNF solution with $C_1 = 0.15$. The dotted line is the solution for stagnant water, which has the same functional form as the BDNF solution, with $C_1 = 0.0735$ inferred from Muellenhoff et al. (1985).

COMMENTS

Several observations can be made from the data shown in Fig. 4. First, the data are distinguished by two groups: one for diffuser discharges (the Miami-Central and Miami-North outfalls) and the other for single-port discharges (the Hollywood and Broward outfalls). At the same H/l_b value, dilution for diffuser discharges is smaller than that for single-port discharges. Reasons for this may be as follows: (1) The port spacings of these diffusers

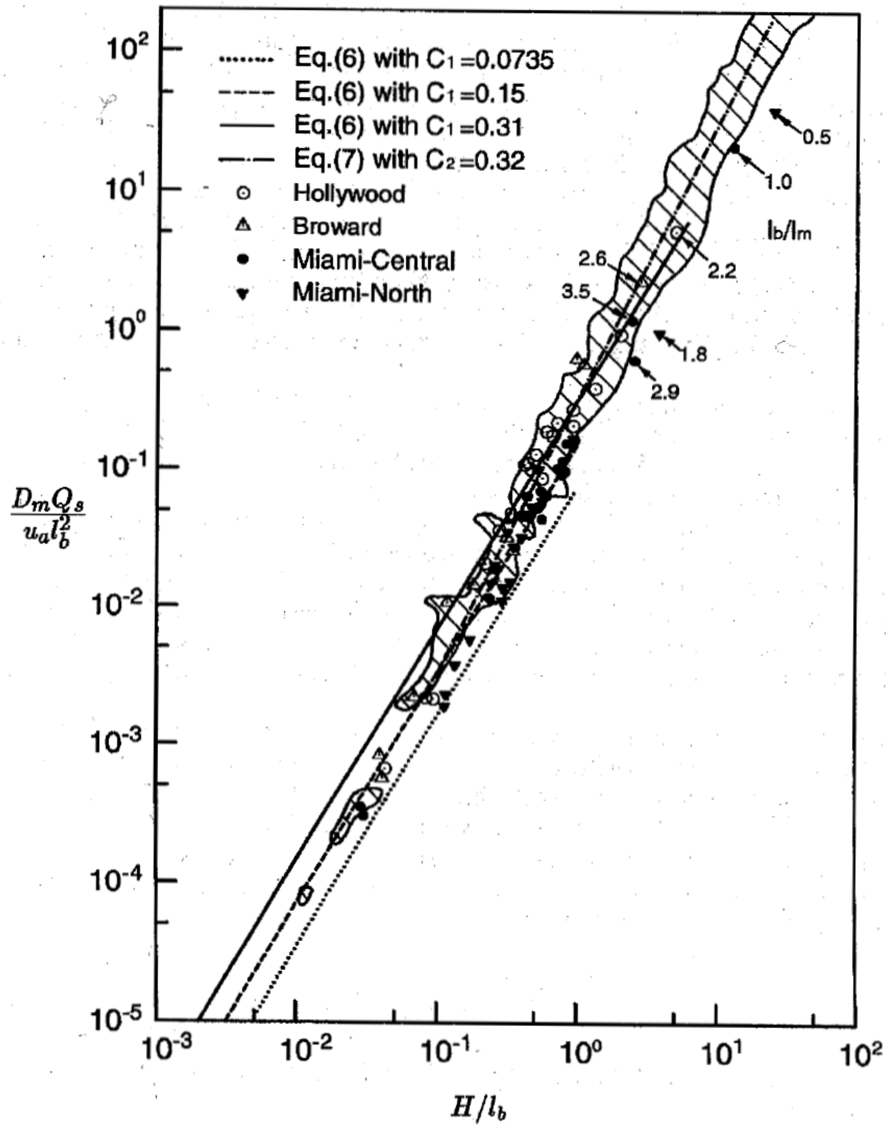

FIG. 4. Correlation of Initial Dilution Data

are not large enough to separate wastefields generated by each port discharge, so partial merging could occur and result in lower dilution; and (2) the wastefield formed by a diffuser discharge is significantly larger than that formed by a single-port discharge, so that the blocking effects of the wastefield on the mixing of rising buoyant jets will be more significant for diffuser discharges than for single-port discharges. In other words, the effective discharge depths for these two outfalls should be less than the discharge depths used in the analysis.

Second, after comparing our data with the data provided by Lee and Neville-Jones (1987) and Wood (1993), shown as shaded areas in Fig. 4 (most of their data are from single-port discharges and only a few are from widely spaced multiport discharges), we found that data points for the Hollywood and Broward outfalls fall into the shaded areas and around the center lines of the shaded areas; data points for the Miami-Central and Miami-North outfalls are located on or off the low boundaries of the shaded areas. This suggests that our data for single-port discharges are consistent with data from previous studies, but the data for multiport diffuser discharges are not. The major reasons for the inconsistency are the partial merging and blocking effects of wastefields, as we have discussed.

Third, we mentioned that an assumption, $l_b/l_m >> 1$, has to be made to utilize (5). Most of the ratios are much greater than the unity (see Tables 2–5). However, some of the ratios are quite small. Seven data points of this ratio that have small values are marked with the ratio values in Fig. 4. Notice that four of these points are quite off the asymptotic solution line for the BDFF. This suggests that l_m may have effects on dilution when l_b/l_m is small.

Another observation from Fig. 4 is that the BDFF solution [(7)] with $C_2 = 0.32$, given by Lee and Neville-Jones (1987), if fairly consistent with all the data for $H/l_b > 0.5$. However, the BDNF solution [(6)] with $C_1 = 0.31$ given by them does not fit well with all the data for $H/l_b < 0.1$. This is because they obtained $C_1 = 0.31$ using their data with H/l_b ranging approximately from 0.1 to 8.0 [Fig. 3; in Lee and Neville-Jones (1987)]. New data from this study and from Wood (1993) are added at H/l_b down to 0.01. To fit all the data for $H/l_b < 0.1$, $C_1 = 0.15$ seems an appropriate value. This value can be compared with an asymptotic value $C_1 = 0.10$ for H/l_b less than about 0.01, found in a recent laboratory test (Lee and Cheung 1991).

In addition, our data show that dilutions were not significantly affected by either the angle of a diffuser to current or the density stratification. These two parameters should and might have some effects on initial dilution, but in the present outfalls their effects were small and within the measurement accuracy of dilutions and of other parameters affecting dilution.

We have seen that both asymptotic solutions for the BDNF and BDFF have a power law relationship as

$$\frac{D_m Q_s}{u_a l_b^2} = a \left(\frac{H}{l_b}\right)^b \tag{8}$$

where a = experimental coefficient; $b = 5/3$ for the BDNF; and $b = 2$ for the BDFF.

It can be assumed that (8) also applies to the transition region between the BDNF and BDFF, so that it can be used to fit the data at any range of H/l_b and resulting b may range from 5/3 to 2. Eq. (8) is then used to obtain semiempirical equations for our outfall discharges using the field data shown in Tables 2–5. Although resulting equations may have less theoretical value than asymptotic solutions, they could be more accurate for dilution prediction for these particular outfalls and of more practical value. Since the data are distinguished by two groups, power regression for data for single-port and diffuser discharges should be done separately. For the Hollywood and Broward outfalls (single-port discharges), the regression yields $a = 0.3355$ and $b = 1.9162$, with a correlation coefficient of 0.9896 ($a = 0.3537$ and $b = 1.9488$ if two marked points that have small l_b/l_m values are not used). For the Miami-Central and Miami-North outfalls (diffuser discharges), the regression yields $a = 0.1648$ and $b = 1.7913$, with a correlation coefficient of 0.9912 ($a = 0.1794$ and $b = 1.8598$ if five marked points that have small l_b/l_m values are not used). Note that the values of b are between 5/3 and 2.

It can then be deduced from the regression results that dilution is related to current speed and buoyancy flux as $D_m \propto u_a^{0.75}B^{0.08}$ for the Hollywood and Broward outfalls, and as $D_m \propto u_a^{0.37}B^{0.21}$ for the Miami-Central and Miami-North outfalls. The deviation of the power in the semiempirical equations from either the BDNF or the BDFF solution may be an indication that most of our data are in the transition region between the BDNF and the BDFF, because in the transition, dilution should be a function of both current speed u_a and effluent buoyancy flux B. In fact, most of our data are in a range of H/l_b from 0.03 to 3.0. A recent laboratory test of Lee and Cheung (1991) indicates that the transition between the BDNF and the BDFF is in a range of H/l_b from 0.01 to 1.0 [Fig. 4; in Lee and Cheung (1991)].

CONCLUSIONS

Initial dilutions of four ocean outfalls on the east coast of South Florida, all located within the western boundary region of the Florida current, were determined from dye and salinity studies. Results show that initial dilutions determined from both methods are consistent. A total of 72 initial dilution data are interpreted using the dimensional analysis method. Data for the Hollywood and Broward outfalls (single-port discharges) are consistent with data from previous studies. Data for the Miami-Central and Miami-North outfalls (multiport diffuser discharges) are not consistent with data for single-port discharges. Based on all available data in the BDNF (for H/l_b as small as 0.01), $C_1 = 0.15$ for the BDNF solution is suggested. This value is smaller than the previous value, $C_1 = 0.31$, given by Lee and Cheung (1987), because $C_1 = 0.31$ was obtained from their data with H/l_b ranging from 0.1 to 8.0. It is also suggested that the BDNF solution apply for $H/l_b \leq 0.1$, and the BDFF solution apply for $H/l_b \geq 0.5$.

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APPENDIX I. DERIVATION OF EQ. (3) AND (4)

Considering a single plume rising from a port, we apply the conservation of salinity for this plume and have

$$S_{ac}\int_0^z E\,dz = \int_0^z ES_a(z)\,dz \tag{9}$$

where z = vertical coordinate measured from the water bottom upward; E = entrainment of ambient water per unit time and per unit height; $E = dq/dz$; and $q(z)$ = volume flux entered to the plume from ambient. q is related to the flux-averaged dilution D_a by

$$D_a = \frac{(q + Q_s)}{Q_s} \tag{10}$$

and D_a is related to the centerline dilution D_c by

$$D_a = \alpha D_c \tag{11}$$

where α is a constant and $\alpha = 1.7$ for a Gaussian profile assumption.

Then, E is written as

$$E = \alpha Q_s \frac{dD_c}{dz} \tag{12}$$

For a simple plume in a moving water, the centerline dilution as a function of z is written as [e.g., Lee and Neville-Jones (1987)]

$$\frac{D_c Q_s}{u_a l_b^2} = C_1\left(\frac{z}{l_b}\right)^{5/3}; \qquad \text{for BDNF} \tag{13}$$

$$\frac{D_c Q_s}{u_a l_b^2} = C_2\left(\frac{z}{l_b}\right)^{2}; \qquad \text{for BDFF} \tag{14}$$

From (12)–(14) we have

$$E = Az^{2/3}; \qquad \text{for BDNF} \tag{15}$$

$$E = Bz; \qquad \text{for BDFF} \tag{16}$$

where $A = 1.667\alpha C_1 u_a l_b^{1/3}$; and $B = 2\alpha C_2 u_a$.

The salinity profile is assumed to be linear and has a functional form

$$S_a(z) = \left(S_{ab} - \frac{S_{ab} - S_{as}}{H}\,z\right) \tag{17}$$

Substituting (15) or (16), and (17) into (9) and performing the integration, we obtain (3) and (4).

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APPENDIX III. NOTATION

The following symbols are used in this paper:

B = effluent buoyancy flux;
C_o = dye concentration in effluent;
C_m = maximum dye concentration in boil;
D_a = flux-averaged dilution;
D_c = plume centerline dilution;
D_m = minimum surface or near-surface dilution;
E = entrainment of ambient water to plume;
g = gravitational acceleration;
g'_o = reduced gravitational acceleration;
H = water depth above discharge;
l_b, l_m = length scales for round buoyant jet;
M = effluent momentum flux;
N = buoyancy frequency;
Q = total effluent discharge rate;
Q_s = effluent discharge rate from port;
S_{ac} = characteristic ambient salinity;
S_{ab} = salinity at bottom;
S_{as} = salinity at water surface;
S_e = effluent salinity;
S_m = minimum salinity in boil;
u = current speed measured at depth;
u_a = characteristic current speed; depth-averaged current speed;
u_j = exiting velocity of single port discharge;
θ = current direction;
ρ_a = ambient density;
ρ_{ao} = characteristic ambient density; depth-averaged ambient density;
ρ_o = effluent density;
ΔS_e = salinity deficit in effluent; and
ΔS_m = maximum salinity deficit in boil.