

Gulf Research Reports

Volume 9 | Issue 1

January 1994

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DOI: 10.18785/grr.0901.06

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Recommended Citation

Gaston, G. R. and K. A. Edds. 1994. Long-Term Study of Benthic Communities on the Continental Shelf Off Cameron, Louisiana: A Review of Brine Effects and Hypoxia. *Gulf Research Reports* 9 (1): 57-64.
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LONG-TERM STUDY OF BENTHIC COMMUNITIES ON THE CONTINENTAL SHELF OFF CAMERON, LOUISIANA: A REVIEW OF BRINE EFFECTS AND HYPOXIA

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ABSTRACT A long-term data set compiled from our studies and a variety of investigations was analyzed to determine the effects of nine years of discharged brine (concentrated salt water) on benthic organisms surrounding a brine diffuser off Cameron, Louisiana (USA). These investigations began three months before brine discharge was initiated in 1981. A preliminary summary by Giammona and Darnell (1990) relied on just three years of discharge data and gave misleading reports of brine impacts.

Brine effects over the nine years of study were minimal, in part because the fine sediments of the study area were numerically dominated by opportunistic species, mostly estuarine taxa, that showed dramatic population fluctuations both spatially and temporally. These fluctuations in benthic densities were the most salient characteristic of the study area. They resulted from summer hypoxia and anoxia in bottom waters, not from brine. The hypoxia was related to Mississippi River discharge and subsequent salinity stratification. Hypoxia eliminated some taxa and severely reduced populations of most benthic species. The only significant differences between communities near the diffuser and those outside the influence of its discharged brine resulted from water-column mixing by the discharged brine, which oxygenated waters around the diffuser and stabilized the salinity of bottom water at the stations near the diffuser. This enhanced benthic diversity around the diffuser and resulted in greater populations during some seasons.

INTRODUCTION

The United States established the Strategic Petroleum Reserve (SPR) following the 1972 Middle East oil embargo to ensure adequate oil reserves and prevent future petroleum shortages in the United States. The SPR designed and implemented a plan for storage of approximately 1 billion bbl of crude oil in underground caverns hollowed from salt domes along the U.S. Gulf Coast. These caverns were created and subsequently enlarged by high-pressure jets of water blasted against cavern walls, producing up to 80 million liters (1 million bbl) of saturated brine per day that was pumped into the ocean.

The purpose of this study was to assess long-term effects of discharged brine on the macrobenthic communities surrounding the diffuser, in water approximately 10 m deep. Giammona and Darnell (1990) reported an impact of brine on the benthic communities during 1981 - 1983, and suggested that the communities might return to background levels once discharge ceased. Gaston *et al.* (1985) studied colonization near the discharge site during 1982, and concluded that there were no obvious effects of brine on functional feeding groups of benthos. Data were collected on benthic communities surrounding the West Hackberry brine diffuser during 1981 - 1984 and 1988 - 1989 to test the hypothesis that the macrobenthic-community species com-

position and taxon abundance in the area of the diffuser returned to background levels by 1988 - 1989 by comparing benthic community data near the diffuser and at several distances away.

Background

The U.S. Department of Energy (DOE) began discharging saturated brine (salt water up to 150 ppt) into the Gulf of Mexico from its SPR West Hackberry site during May 1981. There were several SPR sites established along the Louisiana and Texas coasts. West Hackberry was an SPR site located near Hackberry, Louisiana, just inland of the coastal fishing city of Cameron, Louisiana. Brine was pumped from salt-dome caverns to a holding pond, then to a discharge site in the Gulf of Mexico approximately 11.5 km southwest of Calcasieu Pass, near Cameron, Louisiana. The brine entered the Gulf through diffuser heads at the end of a pipeline. The brine was generally comparable to sea water in ionic ratios, except for slightly higher calcium and slightly lower magnesium concentrations (Jeffrey *et al.*, 1983). Except for short-term shutdowns, the discharge was continuous at rates of 40 to 80 million liters/day until November 1984. Brine flow thereafter occurred irregularly, and discharge volume varied widely through 1989.

However, some discharges occurred every year at rates of up to 80 million liters/day.

The area was first studied for an environmental impact report by Science Applications Incorporated (1976). A second study was conducted by the U.S. Department of Commerce (1981), and a review by Parker *et al.* (1980) included macrobenthic communities surrounding all proposed brine disposal sites in the Gulf of Mexico. A comprehensive study of the local macrobenthic community was conducted by Weston and Gaston (1982), who established the long-term sampling sites during the three months prior to the initiation of brine discharge. The effects of first year brine discharge on the macrobenthic communities were addressed in a multidisciplinary study by Gaston and Weston (1983). Gaston (1985) and Gaston *et al.* (1985) investigated the trophic structure and recolonization capabilities of macrobenthic organisms in the area of the brine plume. Benthic investigations centered on comparisons of community parameters near the diffuser with those at various distances away, including comparisons with reference sites outside the plume of discharged brine.

Gaston and Weston (1983) and Hann *et al.* (1985a) reported a significantly greater abundance of benthic organisms and greater numbers of species near the diffuser, in part due to the elimination of all benthos at sampling sites outside the brine plume during summer hypoxia (Gaston, 1985). Physical mixing of the water column by the diffuser apparently disrupted stratification of the water column and kept the bottom water and sediments around the diffuser oxygenated. Giammona and Darnell (1990) erroneously referred to this discrepancy in community parameters as a "long-term cumulative effect" of discharge, and suggested that benthic communities around the diffuser might return to background levels once brine discharge ceased. We collected data under the auspices of the Louisiana Department of Wildlife and Fisheries (LDWF) during 1988 - 1989.

Study Area

The study area centered around the West Hackberry brine diffuser located on the continental shelf off Cameron, Louisiana (Figure 1).

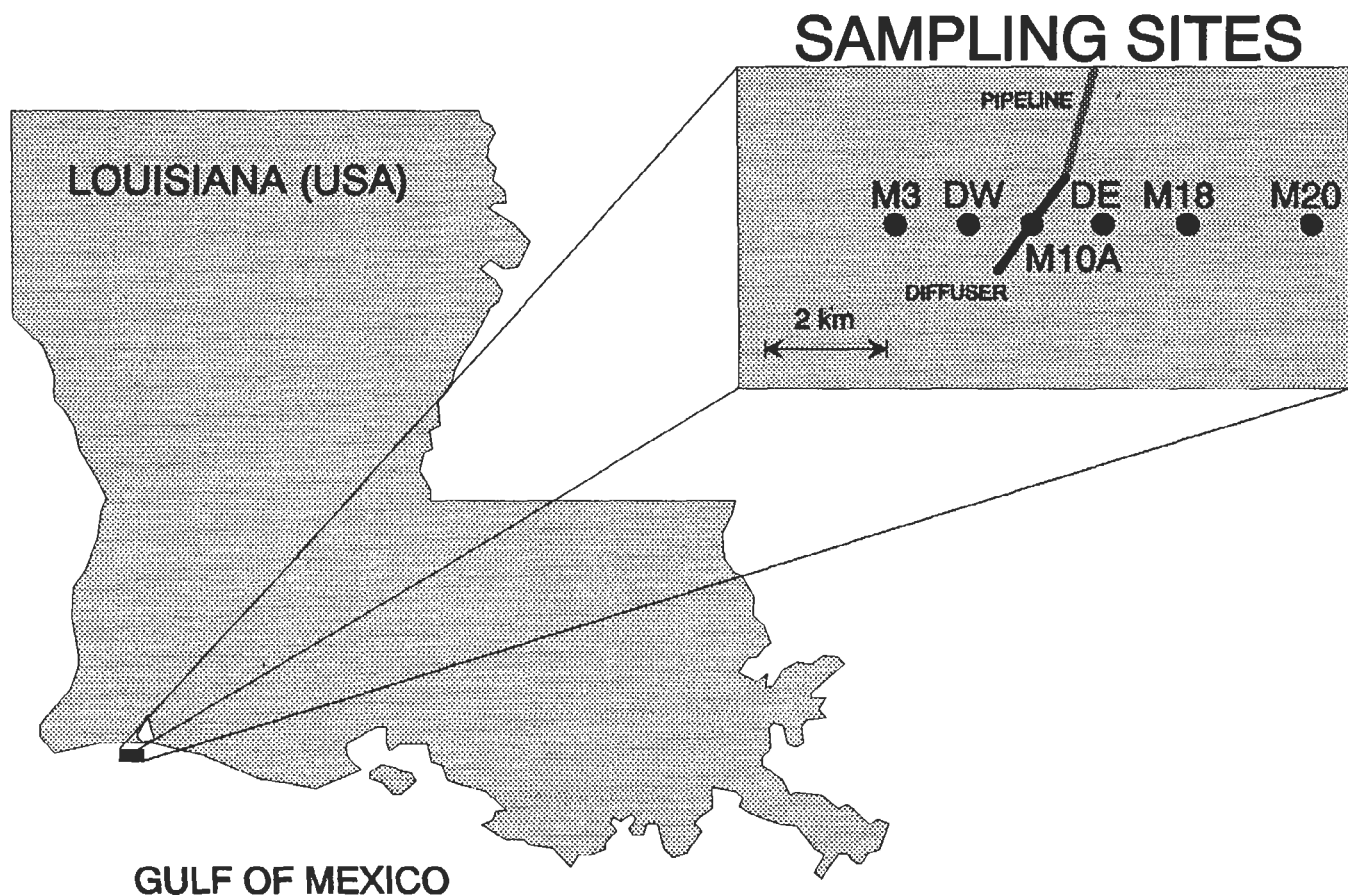


Figure 1. Sampling sites located in a transect across a Strategic Petroleum Reserve (SPR) brine diffuser in the Gulf of Mexico off Cameron, Louisiana. All stations were located at 10-m water depth. Brine was pumped to the diffuser from the West Hackberry SPR facility.

The physical environment of the study area was described by Hann *et al.* (1985a) and Gaston *et al.* (1985). Sediments of the area were generally silty sand (50 - 90% silt-clay). Bottom salinity (15 - 32 ppt) ranged widely with season and tidal cycles, due to the proximity of the Calcasieu, Atchafalaya, and Mississippi Rivers. Temperatures of bottom water varied from winter lows of approximately 12°C to 30°C during the summer. Water currents varied with wind speed and direction, but westerly currents dominated, thereby generally moving the brine plume west of the diffuser site (M10A) and away from the control site (M20) (Gaston and Weston, 1983; Gaston *et al.*, 1985; Hann *et al.*, 1985a).

Bottom oxygen levels during summer months often dropped below 2 ppm (hypoxia) and periodically reached anoxic conditions (Gaston, 1985). Hypoxia occurred during summer months of most years, although it was periodically disrupted by strong winds or storms. Hypoxia had a dramatic effect on benthic communities in the study area, depleting benthic populations, and resulting in domination by relatively small benthos and first-year populations (Gaston, 1985; Gaston *et al.*, 1985).

MATERIALS AND METHODS

Six stations (DE, DW, M3, M10A, M18, and M20) were sampled along an east-west transect across the diffuser (Figure 1). All stations were at 10 m depth. Samples were taken monthly during 1981 and 1982, and less often thereafter. The eastern-most site (Station M20) was located 10 km east of the diffuser, and was outside the effects of discharge (Gaston and Weston, 1983). Station M18 was 5 km east of the diffuser and rarely within the brine plume. The other four sites were within the plume fairly regularly, depending on their distance from the diffuser, the discharge rate, and prevailing currents. Lower water-column salinity near the diffuser was generally 3 - 8 ppt above ambient due to brine discharge (Hann *et al.*, 1985a).

Six replicate samples were taken at each station. Number of replicates necessary to assess the macrobenthic communities of the study area was determined by Gaston and Weston (1983). Samples were taken with a 0.1 m² Smith-McIntyre sediment grab, washed on a 0.5 mm sieve, preserved in buffered formalin in the field, and transferred to 70% ethanol in the laboratory. Most specimens were identified to species.

Statistical analyses included a Model I Analysis of Variance (ANOVA, Sokal and Rohlf, 1981) among stations (when the Bartlett Test indicated homogeneity of variance) using dominant-species densities and total numbers of macrofauna in each replicate as entities. If statistically significant differences were indicated by ANOVA, Duncan's

Multiple Range Tests were used to test for statistical differences ($\alpha = 0.05$) among stations. Additional information concerning the study area, its physical regime, and methods of sampling was provided by Gaston and Weston (1983), Gaston (1985), and Gaston *et al.* (1985).

RESULTS AND DISCUSSION

There were no notable changes in the sedimentary regime of the study area following the initiation of brine discharge (Hann *et al.*, 1985a). Sediments consisted primarily of silty clay to sandy mud, with never more than 48% sand at any site.

During the entire study period, the benthic community was characterized by strong numerical dominance of relatively few species that showed dramatic population fluctuations both spatially and temporally. Most noteworthy among the species that numerically dominated prior to brine discharge were deposit-feeding polychaetes (especially *Sabellides* sp.) and a suspension-feeding phoronid, *Phoronis muelleri* (Weston and Gaston, 1982). Weston and Gaston concluded that the dominance by opportunistic species lessened the potential for assessment of impact from brine, even though there was a general homogeneity of the benthic faunal distributions in the area. Populations of opportunistic species are characterized by wide fluctuations in densities.

During the first year following initiation of brine discharge, the benthic communities showed no changes that could be attributed to brine impact (Weston and Gaston, 1982). The macrobenthic communities of the area were dominated by a rapidly changing suite of young individuals of opportunistic species, mostly detritivores (Gaston and Weston, 1983). Suspension-feeding and deposit-feeding polychaetes, such as *Magelona* cf. *phyllisae*, *Paraprionospio pinnata*, *Mediomastus californiensis*, and *Cirratulus* cf. *filiformis* dominated. Gaston and Weston (1983) reported higher numbers of species and higher populations of some taxa around the brine diffuser ($P \leq 0.05$), believed related to salinity stability near the diffuser. Populations of *M. cf. phyllisae* were significantly higher around the diffuser during six of the twelve months following initiation of discharge. *Mediomastus californiensis* populations were also periodically elevated around the diffuser (Station M10A) during the first year of discharge, but matched background levels thereafter.

There were predictions that discharged brine might be toxic to planktonic larvae of the benthos. Indeed, Vecchione *et al.* (1983) reported reduced numbers of zooplankton and some sublethal effects on zooplankton near the diffuser. Colonization studies of macrobenthos were subsequently conducted by placing defaunated sediment boxes in areas

near the diffuser and outside the brine plume (Gaston *et al.*, 1983; Gaston *et al.*, 1985). These studies indicated that most colonization of the sediments resulted from settling meroplanktonic larvae, the macrobenthos in the area of the brine diffuser rapidly colonized, and no significant differences were found between the diffuser and control sites.

Perhaps the most salient aspect of the West Hackberry SPR diffuser study area was apparent by 1981. The diffuser was located in an area of the northern Gulf of Mexico continental shelf affected by summer hypoxia which annually eliminated much of the benthic community, thus leading to domination by first-year benthos (Gaston, 1985). The dominant species of the area following hypoxic conditions was most commonly the polychaete, *Magelona cf. phyllisae*, perhaps indicative of its tolerance to high levels of hydrogen sulfide and low dissolved oxygen. All of the dominant species in the area were opportunistic species. There was often higher abundance and more species at stations surrounding the diffuser, Station M10A (Tables 1-2). Gaston (1985) proposed that the differences between communities near the diffuser and those outside the brine plume resulted from effects of hypoxia and brine discharge, especially physical mixing of the water column by the diffuser, resulting in breakup of density stratification, and stabilization of the bottom salinity surrounding the diffuser. Salinity stability in an area with widely fluctuating tidal conditions may lead to higher diversities and colonization by more high-salinity taxa (Gaston *et al.*, 1985). As a result, populations of many taxa surrounding the diffuser survived hypoxic events of 1982, and many high-salinity taxa colonized the area around the diffuser (Gaston and Weston, 1983; Gaston, 1985; Gaston *et al.*, 1985).

No major impacts to the macrobenthic community from brine discharge were detected during 1983 - 1984 (Hann *et al.*, 1985a). Summer hypoxia again was the primary factor in structuring benthic communities of the area. Hann *et al.* (1985a) reported that sediments matched predischage conditions, species diversity was highest at the diffuser site, and greater abundance of macrofauna often occurred around the diffuser (Tables 1 - 2). Giammona and Darnell (1990) referred to these differences between diffuser and control sites as an "impact"; however, the term "impact" was misleading, since the effect was a reduced impact from hypoxia, rather than a toxic effect of brine discharge. Giammona and Darnell further hypothesized that benthic-community characteristics should return to background levels once brine discharge ended.

Abundance of macrobenthos in the study area varied widely during 1981 - 1984 (Tables 1 - 2). During the summer of 1981, abundance was reduced by hypoxia at every station, though the effects were generally lessened around the diffuser as evidenced by greater number of taxa surviving at Station M10A (Table 2; Gaston, 1985). Numbers at one site (M3) reached over 20,000 individuals m⁻²

during June 1981, but dropped below 1000 individuals m⁻² elsewhere (M18) following the 1981 summer hypoxia. Hypoxia was not as persistent during summer of 1982; abundance that summer was higher at most stations (2000-3000 individuals m⁻²). Hypoxia again eliminated most macrobenthos during summer of 1983 and 1984, and communities dropped to below 1000 individuals m⁻² at most sites (Hann *et al.*, 1985a).

Macrobenthic densities and taxa collected during summer 1988 - 1989 (Table 3) were similar to those reported soon after the initiation of brine discharge by Gaston and Weston (1983), Hann *et al.* (1985a), Gaston (1985), and Gaston *et al.* (1985). Abundance during summer (1988 - 1989) was low; fewer than 1000 individuals m⁻² occurred at some sites during August 1988. During August 1989, however, densities at all sites exceeded 2000 individuals m⁻², perhaps indicative of lessened effects of hypoxia. There were no differences in numbers of taxa or number of individuals ($P > 0.05$) between diffuser and control stations during 1988; however, there were elevated numbers of individuals around the diffuser during 1989. These 1989 data suggest that the brine diffuser may have enhanced colonization by benthic communities or reduced effects of dissolved oxygen.

Opportunistic species, primarily estuarine polychaetes, were numerically dominant throughout the study, and there were no substantial changes in the functional feeding groups during the nine-year period. Suspension-feeding and deposit-feeding polychaetes, especially *Magelona cf. phyllisae* and *Paraprionospio pinnata*, dominated throughout the study. The phoronid, *Phoronis muelleri*, and polychaetes, *Sabellides* sp. and *Cirratulus cf. filiformis*, that were so abundant during the early 1980s diminished in mean density to below five individuals m⁻² at every site by 1989. Other opportunistic polychaetes, *Cossura soyeri* and *Sigambra tentaculata*, increased in abundance during the late 1980s. Such shifts among dominant taxa are common in many continental shelf macroinvertebrate communities (reviewed by Gaston, 1987; Parker *et al.*, 1980) and was reported in previous investigations of the area (Gaston and Weston, 1983; Gaston, 1985; Gaston *et al.*, 1985).

Large molluscs and other equilibrium (long-lived) species were never collected. Juveniles of the bivalve mollusc, *Mulinia lateralis*, dominated the taxa at most stations during June 1988 (mean of 476 m⁻²; upto 1066 m⁻²), but were eliminated by August 1988 and were not abundant during August 1989. This species often was among the numerically dominant taxa during late winter and spring of the early 1980s, but its populations were eliminated or severely reduced during summer hypoxia (Gaston and Weston, 1983; Gaston, 1985; Hann *et al.*, 1985a). Other molluscs that were severely impacted by hypoxia included *Epitonium* sp., *Anachis obesa*, *Nassarius vibex*, *N. acutus*, and *Macoma mitchelli*. A similar pattern of colonization

TABLE 1

Average abundance ($n = 6$) of macrobenthos (m^{-2}) by month and by year. Collections were made at the West Hackberry brine discharge study area off Cameron, Louisiana. No collection of data is indicated by a dash. Data from Gaston (1985, 1992), Gaston *et al.* (1985), and Hann *et al.* (1985).

1981		FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
M3		2952	6747	10478	14620	21790	6220	4780	2830	2360	2130	71540
DW		3605	3487	4795	4520	3300	2780	2040	1710	1830	1510	1760
M10A		3448	5463	4866	4980	13050	1020	1350	2050	2040	2520	3260
DE		1622	4422	3597	3570	1830	980	1520	1730	2390	1610	2220
M18		1843	4150	4222	3140	4190	2150	670	1680	1380	1940	2080
M20		2808	3533	2445	1410	2740	-	-	2010	1720	1770	1830
1982	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
M3	1890	3320	2740	5610	4753	2438	2360	2809	2062	-	4958	-
DW	1980	2890	3940	4890	4070	3579	1324	2251	1588	-	3621	-
M10A	1960	2940	4740	3910	6767	3575	3061	1420	2418	-	3403	-
DE	3070	4730	4730	5920	7918	4261	2326	3003	2234	-	2704	-
M18	2740	5410	3210	5880	5132	3656	2368	2649	2984	-	2632	-
M20	2910	6780	8840	6230	13280	6844	1951	2019	1622	-	2123	-
1983	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
M3	-	5271	-	-	2428	1348	942	1790	-	-	1185	-
DW	-	11600	-	-	1515	685	857	887	-	-	1635	-
M10A	-	10025	-	-	703	800	1079	907	-	-	1663	-
DE	-	4696	-	-	745	1403	1488	1266	-	-	1579	-
M18	-	18736	-	-	1064	1032	1164	1538	-	-	1425	-
M20	-	2589	-	-	1304	583	952	775	-	-	1246	-
1984	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
M3	-	2038	-	-	541	636	1411	1115	-	-	1046	-
DW	-	2387	-	-	2827	1282	1693	1093	-	-	1523	-
M10A	-	4503	-	-	1057	950	1579	874	-	-	1159	-
DE	-	2287	-	-	1248	1833	2055	1324	-	-	1015	-
M18	-	1877	-	-	782	226	1668	1311	-	-	2368	-
M20	-	1331	-	-	865	2375	743	978	-	-	1862	-

TABLE 2

Number of macrobenthic taxa (total in six replicates) by month and by year. Collections were made at the West Hackberry brine discharge study area off Cameron, Louisiana. No collection of data is indicated by a dash.

1981	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
M3	-	47	51	47	48	47	29	41	50	55	50	54
DW	-	43	42	55	58	65	28	40	40	53	48	49
M10A	-	53	49	50	53	76	35	53	39	48	48	47
DE	-	35	41	53	54	48	36	36	34	52	51	52
M18	-	35	46	49	45	41	28	25	37	40	43	42
M20	-	41	41	39	45	50	-	-	32	42	38	36
1982	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
M3	53	68	56	64	70	52	43	54	49	-	61	-
DW	42	49	53	49	46	36	36	53	41	-	45	-
M10A	49	50	48	52	54	49	59	50	56	-	47	-
DE	46	47	65	49	49	40	47	52	44	-	46	-
M18	47	53	40	51	47	29	46	42	46	-	36	-
M20	47	49	54	45	56	47	38	48	44	-	44	-
1983	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
M3	-	64	-	-	37	18	12	24	-	-	61	-
DW	-	50	-	-	26	23	23	23	-	-	53	-
M10A	-	60	-	-	24	32	46	31	-	-	66	-
DE	-	41	-	-	23	31	23	26	-	-	43	-
M18	-	40	-	-	23	25	19	18	-	-	49	-
M20	-	41	-	-	25	21	16	25	-	-	44	-
1984	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
M3	-	85	-	-	54	71	39	43	-	-	61	-
DW	-	65	-	-	37	34	39	39	-	-	24	-
M10A	-	78	-	-	49	48	66	73	-	-	65	-
DE	-	65	-	-	36	34	61	43	-	-	36	-
M18	-	54	-	-	37	48	49	29	-	-	24	-
M20	-	56	-	-	29	34	29	26	-	-	26	-

TABLE 3

Number of macrobenthic taxa (total in six replicates) and mean densities (m^{-2}) at six stations during sampling periods in 1988 and 1989. Collections were made at the West Hackberry brine discharge study area off Cameron, Louisiana. Values with similar superscript letters are not significantly different ($P > 0.05$).

		M3	DW	M10A	DE	M18	M20
June 1988	TAXA	58	63	43	57	37	42
	INDIV.	3372	3898	2065	3543	1660	1962
August 1988	TAXA	38	28	37	42	48	45
	INDIV.	977	872	1245	983	1530	1028
August 1989	TAXA	26	32	27	24	25	27
	INDIV.	2080 ^a	3945 ^a	5200 ^b	2775 ^a	4918 ^{ab}	3027 ^a

followed by elimination occurred among the brittle star species, *Hemipholis elongata*, which had been very abundant during the June 1988 sampling (mean of 460 m^{-2} ; up to 606 m^{-2}), but was completely eliminated by August 1989.

CONCLUSIONS

Macrobenthic communities in the study area were not catastrophically impacted by brine discharge as was predicted (Science Applications Incorporated, 1976) before brine discharge began. It appeared that discharged brine had only minor effects on the macrobenthos of the West Hackberry SPR brine diffuser study area, and those effects were mostly enhancements of the benthic communities. Indeed, the only significant differences between communities near the brine diffuser and those outside the influence of its discharged brine resulted from turbulent mixing of the water column by the discharged water, which apparently also affected zooplankton (Vecchione *et al.*, 1983), decreased effects of hypoxia around the diffuser (Gaston, 1985), and stabilized the lower water-column salinity at the station closest to the diffuser (M10A) (Gaston *et al.*, 1985). Similarly, Hann *et al.* (1985b) found fewer species and lower abundance of benthos around the Bryan Mound diffuser during 1983 - 1984 and an enhancement of the communities at the near-field sites, but few consistent patterns of impacts of brine on the macrobenthos.

The hypothesis posed by Giammona and Darnell (1990) that benthic communities might return to background levels after brine discharge ended was erroneous.

Benthic communities surrounding the diffuser often matched background (control site) levels during discharge. Physical mixing of the water column and salinity stability due to brine discharge, both enhancement features of discharge operations, were the primary features that distinguished impact from control sites. Those distinctions resulted from greater densities of benthos within the affected area of the diffuser. Benthic communities around the diffuser did match background levels, except when those enhancement characteristics were in play.

The West Hackberry study area may be unique in many ways, and probably should not be used solely as an example of the potential for brine effects in other areas. Other offshore brine discharge sites were probably not so fortuitously placed. The Bryan Mound SPR site off Freeport, Texas was located in deeper water (21 m depth), had a more diverse and well-established macrobenthic community, and was not affected annually by hypoxia (Hann *et al.*, 1985b).

Summer hypoxia in the West Hackberry study area, without question, was the primary factor in structuring benthic communities. Hypoxia occurred almost annually, and so severely affected the benthic communities of the study area that brine effects were difficult to assess, especially since the brine effects appeared to be minimal. Hypoxia led to wide seasonal variations in populations of macrobenthos in the study area, and confounded year-to-year comparisons of brine effects (Gaston, 1985; Gaston *et al.*, 1985). Gaston *et al.* (1985) used the colonization study to investigate brine effects within the immediate area of the diffuser, and concluded that effects of brine were minor compared to the impact of hypoxia.

This study emphasized the necessity of long-term assessments of potential contaminants on benthic communities. The analyses were especially enhanced by multidisciplinary research projects in the area, manipulative studies of brine effects on colonization potential of settling larvae, investigations on macrobenthic functional-feeding groups, and intensified sampling efforts during hypoxic events that helped distinguish the effects of brine and hypoxia.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the help of personnel at McNeese State University, especially D. Weston, M. Walther, P. Rutledge and L. DeRouen. We are grateful to A. McAllister and C. Lehner at the University of Mississippi, personnel at the Louisiana Department of Wildlife and Fisheries, especially J. Hanifen, K. Foote and B. Barrett, and personnel at the U.S. Department of Energy (DOE), especially M. Smith. This project was funded by a grant from DOE to the Louisiana Department of Wildlife and Fisheries (LDWF). LDWF subsequently funded research at McNeese State University and the University of Mississippi.

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