Simulation of a storm event in marine microcosms

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ABSTRACT

A storm of moderate intensity and lasting for 14 hours was simulated in three of the Marine Ecosystems Research Laboratory (MERL) microcosms by increasing the intensity of microcosm mixing. The simulation resuspended ~0.3 cm of sediment and increased suspended particulate loads by 2 orders of magnitude. Concurrently, the concentrations of metals and nutrients increased in the water column. Dissolved metals, but not dissolved nutrients, could have been derived from the pore waters of the resuspended sediment. Pore waters would have to have been flushed to a depth greater than 1 cm to explain the observed nutrient increases. More likely, remineralization on the benthos and in the water column combined with reduced photosynthesis account for the slight increase observed in nutrient concentrations. Levels of suspended particulates, nutrients and metals returned to near pre-storm values within 5 days. No long-term effects on biological processes were observed as a result of the storm.

1. Introduction

The effects of storms on geological processes have always been apparent. Storms cause coast line erosion (Koppleman *et al.,* 1976); transport coarse grained sediments (McGowan and Scott, 1975; Hayes, 1978); and increase suspended loads (Bohlen, 1974; Conomos and Peterson, 1976). Storms undoubtedly affect the dispersion of pollutants in nearshore coastal waters, but this problem is not usually addressed in discussions of horizontal and vertical mixing effects on the dispersion of pollutants (e.g., Okubo, 1971). In Narragansett Bay, Rhode Island, we observed a tremendous phytoplankton bloom (~100 μg Chl/l) in August 1976 after the passage of Hurricane Belle but no cause and effect relationship was established (Oviatt *et al.,* 1979). Storm processes are also thought to enhance the exchange of dissolved species of nutrients and metals across the sediment water interface but no quantitative assessments have been made (Bricker and Troup, 1975; Duinker, 1975). Devastating effects by storms on benthic communities are inherently likely

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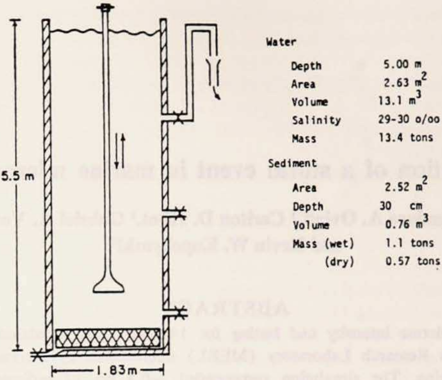

Figure 1. Cross section of one of the 12 MERL microcosm tanks showing the mixer, sediment container, and certain physical characteristics. Arrows indicate mixing by the plunger and water flow. The x's show location of valves.

and have been observed (McCall, 1977), but sampling difficulties have prevented any measurement of storm effects on water column biology.

Controlled microcosms at the Marine Ecosystems Research Laboratory (MERL) encapsulate natural ecosystems. In them, sampling logistics are minimized and impacts of storm resuspension on the benthos and overyling water column can be studied more easily than in the natural system. The storm simulation at MERL was carried out as part of a long-term environmental study of the relationship between water and benthos. In particular, we wished to determine whether the resuspension of sediment by the storm would introduce chemicals into the water column and to observe the duration of any biological effects.

2. Methods

The facility. The MERL microcosms (Fig. 1) are cylindrical enclosures 1.83 m in diameter containing a 5 m column of water overlying 30 cm of natural benthos (see Pilson *et al.*, 1977; and Pilson *et al.*, 1979). They are scaled to mimic a temperate estuary such as Narragansett Bay as closely as possible in sunlight regime, mixing, water exchange, temperature and benthic communities. Bay water flows to the tanks for 10 minutes out of every 6 hours during periods of tank mixing. This provides a water turnover time of 27 days. Sediments and associated soft-bottom benthic community were obtained with a Van Veen grab from central Narragansett Bay during September 1977. Primary productivity, nutrient concentrations, sediment pore water profiles and other variables in the microcosms were similar to lower Narragansett Bay (Pilson *et al.*, 1980; Oviatt *et al*, 1981; Hunt and Smith, 1981; Pilson *et al.*, 1981).

The storm simulation. The tanks are normally mixed by a plunger which turns in an elliptical orbit at 5 rpm on a schedule of 2 hours on - 4 hours off, simulating the intensity and timing of tidal currents. The scaling criterion was that this intensity of mixing would resuspend bottom sediments to levels similar to those observed in Narragansett Bay. During 1978, the annual time weighted mean for suspended load was 3.2 mg l^{-1} in control microcosms and 5.1 mg l^{-1} in the lower west passage of Narragansett Bay. From 0600 to 2030 on July 26, 1978 when the mean water temperature was 23°C, three tanks (3,4,6) were mixed at a higher rate during the intervals when tank mixers were normally off and at the regular rate during normal mixing periods to simulate the varying intensity of storm surges (Hayes, 1978). During the experiment two paddles were added to the mixer shaft at the water surface and the mixers rotated at approximately 14 rpm during fast mixing. The maximum vertical velocity of the mixer increased from 15.1 cm/sec at 5 rpm to 44.0 cm/sec at 14 rpm or more than double the orbital velocity needed to resuspend bottom sediments (Oviatt and Nixon, 1975; Rhoads *et al.,* 1978). Wave heights and periods necessary to generate these orbital velocities would occur only during storms and only in the lower portions of Narragansett Bay (Oviatt and Nixon, 1975). Three tanks with normal mixing (1,5,8) acted as controls for the experiment. Suspended sediment concentrations, light extinction measurements, oxygen diffusion rates and gypsum dissolution rates (Nixon *et al.,* 1980a) were used to scale the intensity of the simulated storm.

Sampling. The general schedule of sampling is summarized in Table 1.

Suspended material concentrations were determined by filtering water through pretared 0.4 μm Nuclepore filters; the retained particulates were air dried and weighed (C.V., $\pm$ 5%). Samples were taken every two hours during the storm simulation at 0.2 and 4.5 meters in the tank.

Concentrations of dissolved Mn, Fe, Cu, Cd and Pb and particulate Mn, Fe, Cu, Cd, Pb and Al as well as total acid leachable Mn were determined in the water column at intervals during the experiment, up to 36 hours after the storm and again 4 days later. Samples were extracted with APDC-MIBK and analyzed by graphite furnace atomic adsorption spectrometry (Brooks *et al.,* 1967; Piotrowitz, 1977) using high purity methods outlined in Patterson and Settle (1976). Manganese was measured by direct analysis of seawater using graphite furnace atomic adsorption spectrometry (Segar and Cantillo, 1975; McArthur, 1977).

Water column samples were taken from homogeneously mixed tanks before, during and after the storm for fluorometric determinations of chlorophyll *a* (Holm-Hansen *et al.,* 1965; Lorenzen, 1965) and autoanalyzer colorimetric determinations of ammonia, nitrate plus nitrite, phosphate and silicate (Degobbis, 1973;

Table 1. Sampling schedule from 3 microcosms used for a storm simulation in 1978.

	7/17	7/25	7/26 "storm"	7/27	7/28	8/1
Suspended load		X	X	X		X
Metals						
Dissolved Mn, Fe, Cu, Cd, Pb		X		X		X
Total acid leachable Mn		X	X	X	X	X
Particulate Al		X		X		X
Phytoplankton counts		X	X	X		
Chlorophyll *a*		X	X	X		X
Nutrients		X	X	X		X
Zooplankton numbers and biomass		X				X
Total system metabolism		X		X		
Phytoplankton production and respiration		X		X		
^{14}C Phytoplankton production		X	X			X
Benthic fluxes	X			X		
Light extinction coefficient			X			
Oxygen diffusion		X	X	X		
Gypsum dissolution			X			

Frederick and Whitledge, 1972; Solorzano, 1969). Vertical tows were made one day before and five days after the storm for zooplankton numbers and biomass (Tranter, 1968; Steedman, 1976).

Total system metabolism was measured by the diel curve method (Odum and Hoskins, 1958) in tanks 3 and 6. Water samples for oxygen concentration by the methods of Strickland and Parsons (1968) were taken every four hours. Phytoplankton production and respiration were determined by both Winkler titrations (light and dark bottles hung at 1 m depth) and ^{14}C (incubated at 1 m or in a light gradient box as noted). Benthic respiration (Strickland and Parsons, 1968), and release of ammonia (Degobbis, 1973; Solorzano, 1969) and manganese were measured in tank 4 with an *in situ* benthic chamber, which encloses the entire sediment surface on 7/17 and 7/27.

Light extinction coefficients (k) were measured the day before, during and the day after the simulation. Readings were made in $\mu E\ m^{-2}\ sec^{-1}$ at the surface and at 5 depths with a quantum sensor. The extinction coefficient (k) was calculated from an exponential curve fit to the measured data. Percent transmission was measured during the experiment with a transmissometer with a 1 m beam length. The flux of oxygen across the air-water interface was measured in tank 6 during the storm for comparison with previous measurements and to provide a relative measure of the mixing intensity (Nixon *et al.*, 1980a; Rocques, pers. comm.). The flux measurements were made using a floating plastic dome that had been flushed with nitrogen gas. The partial pressure of oxygen in the dome and in the water was monitored over time and the gas flux across the air-water interface

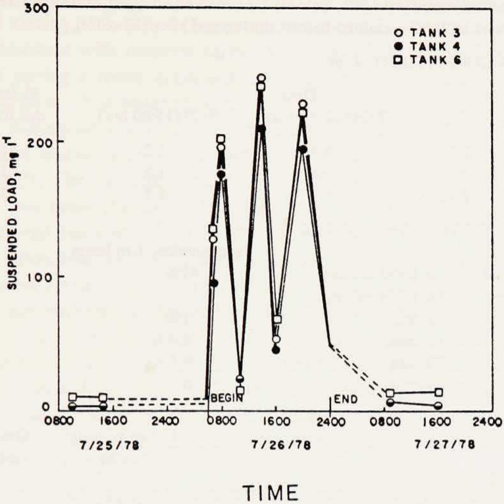

Figure 2. Suspended load in the surface of tanks 3, 4 and 6 during storm simulation during July 25, 26 and 27.

evaluated as a function of the concentration gradient. From these data exchange constants were calculated. The dissolution rates of gypsum blocks (~2.5 × 1.8 × 0.7 cm) were used to provide a rough measure of turbulence for comparison to previous studies at 6°C. Three replicate blocks were positioned at 4 depths in the tanks during the intense mixing. Weight losses resulting from dissolution were corrected to 6°C using a derived relationship between temperature and weight loss at zero turbulence. The gypsum blocks in the storm experiment were also smaller than those used previously and dissolved 36% faster than blocks used in the previous tank and bay measurements. As a result the dissolution rates were also corrected for the effects of size. The temperature and size corrected dissolution rates from the storm experiment were compared with earlier data gathered in the tanks at 5 rpm and in Narragansett Bay.

3. Results

Physical properties. The pre-storm suspended loads were about 1.0 mg/l in tanks 3 and 4 and 8 mg/1 in tank 6. Within the first 90 minutes of the storm the suspended loads reached approximately 200 mg/l at the top of the water column (Fig. 2). At the end of the subsequent 2 hour normal mixing cycle suspended loads

Table 2. Extinction coefficients (k), percent transmission, oxygen diffusion rates and gypsum dissolution rates at 23°C measured before, during and after the storm.

EXTINCTION COEFFICIENT, k/m

	Date			% increase
Tank	7/25	7/26(14:50 hrs)	7/27(15:00 hrs)	due to storm
3	0.79	5.3	1.2	571%
4	0.90	6.4	1.3	611%
6	1.32	6.3	1.7	377%

PERCENT LIGHT TRANSMISSION, %

		Transmission, 1 m beam
Control	5 RPM mixing	49%
Storm	14 RPM mixing	
	5 min.	1%
	10 min.	0.4%
	20 min.	0.1%
	40 min.	0

DIFFUSION

	Piston velocity cm/hr	Oxygen diffusion $gmO_2/m^2/hr/atm$
Narragansett Bay		
Wind 1-4 m/sec, 20°C	4-12	1.7-5.2
MERL Microcosms, 23°C		
Control, Mixer off	0.6	0.3
Control, 5 RPM mixing	1.4	0.6
Control, on-off cycle, 6 hour av.	1.0	0.4
Storm, 5 RPM, surface paddle on regular mixer	3.2	1.0
Storm, 14 RPM, surface paddle on regular mixer	5.9	1.8

GYPSUM DISSOLUTION

	$\bar{x}$ % loss/hr (S.D.)		% increase
Depth	Control, 5.1 rpm	Storm, 14.4 rpm	due to storm
1m	3.83 (.47)	5.03 (.21)	31.3
2m	2.87 (.66)	4.00 (.27)	39.4
3m	2.38 (.26)	4.34 (.22)	82.4
4.5m	2.68 (.36)	5.76 (.22)	114.9

had decreased to about 20 mg/l at the surface (Fig. 2) and 30-50 mg/l at the bottom. Maximum suspended loads observed were ~270 mg/l at 4.5 m. From these concentrations it was calculated that about 0.29 cm of sediment was lifted from the bottom in all tanks.

Suspended load concentrations in the tanks declined following the storm, reaching within a factor of 10 the pre-storm levels in 12 hours. The concentrations continued to decline during the next 6 hours and returned to pre-storm levels by the next regular monitoring period, 5 days later. The loss in suspended loads during both normal mixing periods and the non-mixed period following the storm simulation were consistent with removal times of 3.3 hrs predicted by Stokes equations for particles having a mean grain size of 0.028 mm (determined for these sediments) falling from a 5 m water column.

The high suspended loads caused high extinction coefficients and a reduction in percent light transmission approaching 0 within 40 minutes of the start of the storm (Table 2). The extinction coefficient in tank 6 was much higher than that in the other two tanks the day before the storm (7/25), due to a phytoplankton bloom which had been occurring in tank 6 for several days. The day after the experiment, extinction coefficients were still 130% (tank 6) to 150% (tank 3) of values measured the day before the experiment.

Air-water gas exchange constants were measured in both Narragansett Bay and in the microcosms during various mixing modes (Table 2). During the storm simulation with mixing at 14 rpm the diffusion flux in the microcosms was about 5 times greater than during normal, 5 rpm mixing, and about 6 times greater than during an averaged, on-off mixing cycle. The storm diffusion flux was, however, at the lower end of the values measured for Narragansett Bay during calm conditions (Nixon *et al.*, 1979).

Dissolution rates of gypsum blocks were measured to provide a relative measure of turbulence during the storm (Nixon *et al.*, 1979; Nixon *et al.*, 1980a). Measurements made at 5 rpm with the surface paddle and those made at 14 rpm with the surface paddle showed significantly higher weight loss rates for the latter, particularly at the bottom of the tank where the plunger is located (Table 2). The temperature and size corrected dissolution rates at 5 rpm compare well with previous rates made at 5 rpm in the tanks (Fig. 3). While storm dissolution rates were roughly double those at the 5 rpm mixing speed, they were much lower than rates measured in Narragansett Bay.

Metals. Generally the concentration of dissolved metals increased during the storm. Dissolved Mn increased during the initial 2 hours of the storm by 30-40%. After this initial increase, dissolved Mn concentrations remained constant in tanks 3 and 4 but decreased in tank 6 (Fig. 4). These results, taken in combination with suspended load measurements, suggest that the total depth of disturbed sediment did not increase greatly after the first two hours of the storm. The dissolved Mn benthic flux in tank 4 was 5.8 ± 0.3 μmoles/m^2/hr before the storm and 5.3 ± 0.3 μmoles/m^2/hr after the storm (12 hours) indicating that Mn flux was not greatly altered by the storm or at least reestablished itself quickly.

The total acid leachable Mn also increased during the storm. Maximum concentrations reached were 600 nM in tank 3, about 400 nM in tank 4 and an intermediate concentration in tank 6 (Fig. 4). The concentration of total acid leachable

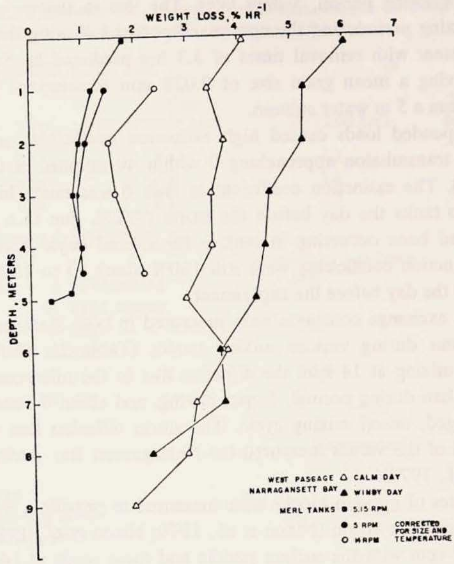

Figure 3. Gypsum weight loss versus water depth during normal and storm mixing in a microcosm and in Narragansett Bay. Storm dissolution rates at 23°C have been corrected to 6°C bay temperature using a standard curve. A size correction has also been made.

Mn returned to near pre-storm levels within 2 hours of the end of fast mixing rate and to pre-storm levels within 12 hours. The increase in particle associated Mn in the water column during the storm is consistent with resuspension of a ~0.2 cm sediment layer having ~160 μg Mn/g (1N HNO_3 leachable) as these sediments have. It is also evident that Mn associated with the sediment particles was rapidly returned to the sediment as the particles deposited.

Dissolved Fe, Pb, Cu and Cd were also released from sediment during the storm disturbance (Table 3). Fe and Pb concentrations increased by 100 to 200% during the storm. Dissolved Cu declined in the first 7 hours then increased to 150% of the pre-storm concentrations over the next 8 hours. Dissolved Cd concentrations did not change greatly during the storm, but increased during the 12 hours following the storm in tanks 4 and 6. Iron responded similarly in tanks 4 and 6 as did Pb in tank 4. Within 5 days all four dissolved metals had returned to pre-storm concentrations. This rapid removal is in accordance with metal removal times for particle reactive metals measured in other MERL microcosms by Santschi *et al.*

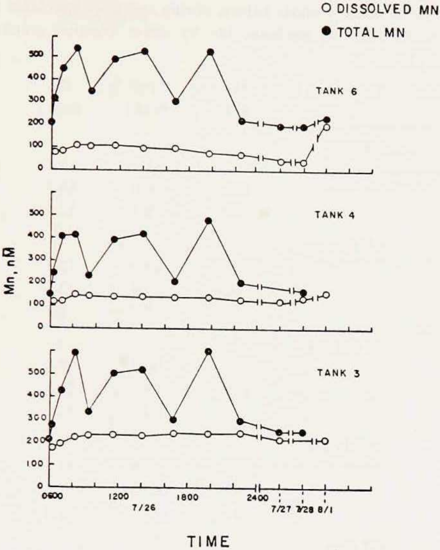

Figure 4. Total acid leachable and dissolved Mn concentrations in tanks 3, 4, and 6 during and after storm simulation, July 26, 1978.

(1980). Note that rapid settling of resuspended bottom sediment during and after the storm did not immediately remove dissolved metals from the water column (Table 3, Fig. 4).

The relative concentrations of organic matter in the water columns for the three storm tanks and the reactiveness of the dissolved metal species may explain observed lags in the concentration of dissolved metals during and after the storm simulation (Hunt, 1979; Hunt and Smith, 1980). In tank 6, which had the highest chlorophyll concentrations (Fig. 5), dissolved metals were lower initially than in tanks 3 and 4 (Table 3). In tank 6, the increase in the dissolved metal concentrations, resulting from the storm, tended to lag tanks 3 and 4. Iron, Pb and Cd reached considerably higher concentrations by the end of the storm in tank 6 than in tanks 3 and 4. However, dissolved Mn remained lower throughout the experiment in tank 6. It may be inferred that the high organic loading in tank 6 affected in some unknown manner both the concentration of metals in the water column and the rate of removal after the storm.

Table 3. Dissolved metal concentrations before, during and after simulated storm. Fe, Cu, Pb, Cd extracted by APDC/MIBK methods. Mn by direct injection graphite furnace atomic adsorption spectrophotometry.

Microcosms and Dates	Time from Start	Mn (nM)	Fe (nM)	Cu (nM)	Pb (nM)	Cd (nM)
July 25	Start					
T3		176	15.1	16.1	0.75	1.71
T4		116	16.0	16.7	0.38	1.02
T6		77	8.5	13.4	0.56	0.86
July 26	+7.5 hours					
T3		229	20.9	12.2	1.25	1.5
T4		140	20.4	12.6	1.56	1.3
T6		100	10.3	7.7	1.30	0.67
July 26	+14 hours					
T3		241	36.7	27.6	2.87	3.6
T4		126	27.7	22.6	2.20	2.0
T6		77	60	21.8	20.4	1.4
July 27	+26 hours					
T3		228	38.9	33.2	3.0	3.9
T4		140	68.9	14.1	4.49	5.9
T6		35	187	17.4	13.0	21.0
August 1	+7 days					
T3		217	14.2	9.7	0.55	1.5
T4		168	17.5	13.3	0.64	1.3
T6		207	9.9	10.1	0.81	0.91

Biological processes. Effects on biological processes were transitory. Generally levels of chlorophyll and nutrients increased during the simulation (Fig. 5). The increase in nutrients was insignificant compared to normal changes in nutrient concentrations over a several day period (Fig. 5). However, the consistency with which the increases occurred suggests that they were real, as the various species of phosphorous exemplifies (Fig. 6). Dissolved inorganic phosphate showed the largest increase although other species also increase the day after the storm. In the other two storm tanks concentrations of all species dropped, but remained generally elevated over pre-storm levels.

Chlorophyll tended to decrease in all three storm tanks in the days following the simulation, particularly in tank 6 which had been blooming for several days prior to the experiment (Fig. 5, Tables 4 and 5). As a consequence of the decline in chlorophyll and remineralization on the bottom, nutrients rose (particularly in tank 6) several days after the storm simulation (Fig. 5). The decline in chlorophyll may or may not have been due to the storm since declines also occurred in control tanks (Table 4).

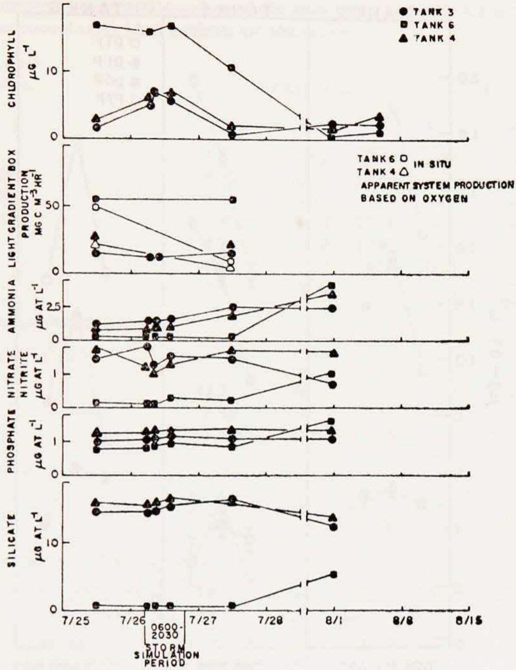

Figure 5. Chlorophyll, production, and nutrient concentrations in the 3 storm simulation tanks before, during and after the experiment.

Metabolism changes also generally decreased after the storm (Table 5). Phytoplankton production incubated in a light gradient box decreased in tanks 3 and 4, but samples from tank 6 showed enhanced production by ^{14}C uptake. However, oxygen measurements in tank 6 showed that production in the whole tank decreased, suggesting that circumstances in the light gradient box were more favorable for the continuation of plant growth (Tables 4 and 5). Benthic metabolism increased by 10% and ammonia flux increased by 20%, presumably due to the increased input of organic matter from the overlying water column (as evidenced by decreased chlorophyll concentrations (Tables 4 and 5). The resuspension of reduced sediments caused oxygen concentrations to drop considerably (Fig. 7). If 2000 cm^3/cm^2 of reduced surface sediment were resuspended during

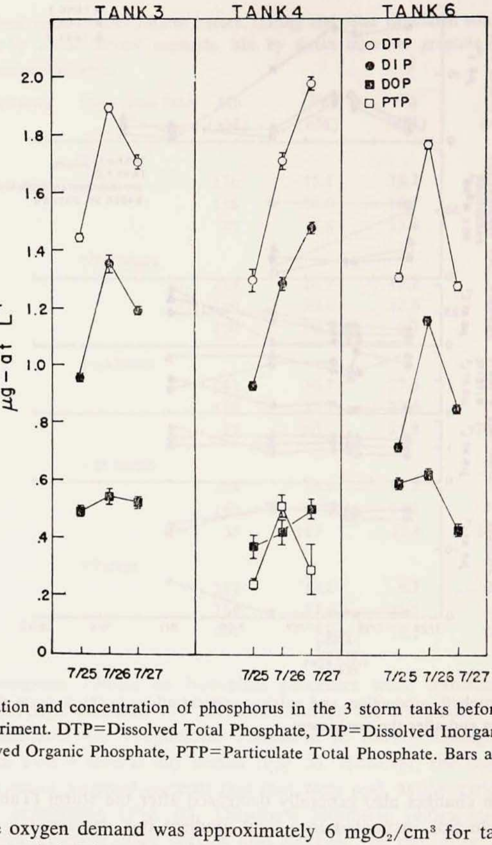

Figure 6. Speciation and concentration of phosphorus in the 3 storm tanks before, during and after the experiment. DTP=Dissolved Total Phosphate, DIP=Dissolved Inorganic Phosphate, DOP=Dissolved Organic Phosphate, PTP=Particulate Total Phosphate. Bars are ± standard deviation

the storm, the oxygen demand was approximately 6 mgO_2/cm^3 for tank 6 and 2 mgO_2/cm^3 for tank 3. The greater demand of tank 6 sediments was probably due to recently deposited phytoplankton from the overlying bloom in the water column. Total system metabolism also declined (Table 5). One week after the storm chlorophyll concentrations increased again in tanks 3 and 4, but continued to decrease in tank 6. Two weeks after the storm chlorophyll increased slightly in all three storm tanks. Treatment and control tanks were similar one week and two weeks after the experiment (Table 4).

No dramatic differences occurred in zooplankton during the storm simulation (Table 6). The range of zooplankton concentrations found in the storm tanks

Table 4. Chlorophyll concentration and metabolic rates before and after the storm simulation. Values from control tanks when available are also shown.

Chlorophyll, $\mu g/1$ Microcosms:	Experimental			Control		
Date	3	4	6	1	5	8
7/25/78	1.93	2.01	17.26	1.40	5.34	5.34
7/26/78, 0700	5.06	6.43	15.81	—	—	—
, 0750	7.73	—	—	—	—	—
, 1430	6.57	6.63	16.84	—	—	—
7/27/78	1.14	1.40	10.80	—	—	—
8/1/78	2.26	1.57	0.82	0.55	2.80	2.05
8/8/78	2.53	2.78	1.61	1.85	1.89	1.31
Phytoplankton production at 1 m						
a. C-14, mg $C/m^3/hr$-						
7/25/78	12.3	20.0	4.78	5.41	34.14	5.44
7/26/78	9.86*	—	—	—	—	—
7/27/78	10.62*	11.98*	46.18*	—	—	—
b. O_2, $mgO_2/m^3/hr$						
7/25/78	49.0	—	216.0	—	—	—
7/27/78	32.0	—	136.0	—	—	—
Benthic respiration and ammonia release						
Before 7/26/78, O_2, $mgO_2/m^2/hr$	74	44	50	74	101	48
, NH_4, μg at$/m^2/hr$	242	162	−13	203	182	202
After 7/26/78, O_2 $mgO_2/m^2/hr$	—	48	—	—	—	—
, NH_4 μg at$/m^2/hr$	—	193	—	—	—	—

Total system metabolism, g $O_2/m^2/day$

Microcosms:	Experimental				Control		
Date / Production	3	4	6	Date	1	5	8
7/25/78	2.53	—	6.41	7/20/78	—	0.12	—
7/27/78	1.34	—	1.45				
Respiration							
7/25/78	3.75	—	4.87	7/20/78	—	0.15	—
7/27/78	2.95	—	2.82				

* Incubated in a light gradient box under fluorescent light.

were similar to the range occurring in the control tanks and the bay. We conclude the short term high concentrations of resuspended sediment had no deliterious effects on zooplankton.

Table 5. Chlorophyll and metabolism changes after the storm simulation calculated from Table 4.

Microcosm		3	4	6
Chlorophyll, 7/25-7/27/78		−40%	−30%	−37%
Phytoplankton production, 7/25-7/27/78				
	C-14	−14%	−40%	+10%
	O_2	−35%	—	−37%
Benthic respiration and ammonia release before and after 7/26/78				
	O_2	—	increase 10%	—
	NH_4	—	+20%	—
Total system metabolism, 7/25-7/27/78				
	Production	−47%	—	−77%
	Respiration	decrease 21%	—	decrease 42%

4. Discussion

Storm simulation. We did not know beforehand how well the simulated storm would match natural storm intensities although it was clear, due to the diameter of the microcosms, that storm intensities of horizontal advection could not be simulated. The values for suspended load during the simulations were above those reported for Narragansett Bay under non-storm circumstances, but they were

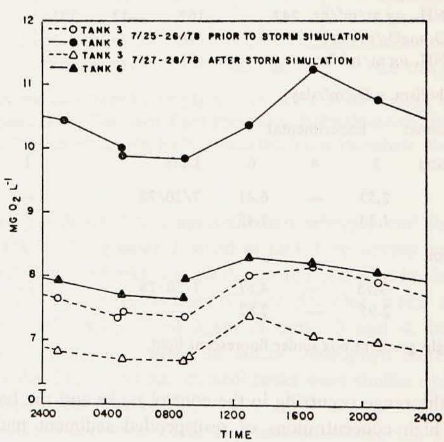

Figure 7. Diel oxygen concentrations before and after the storm simulation in tanks 3 and 6.

Table 6. Zooplankton before and after the storm simulation on 7/26.

	Biomass, g dry wt/m³			Numbers, animals/m³	
Storm tanks	**7/24**	**7/24**	**8/1**	**7/24**	**8/1**
3	.025	.030	.056	10,700	24,800
4	.039	.039	.048	20,000	25,300
6	.047	.053	.033	35,600	9,200
Control tanks					
1	.034		.048	20,300	25,100
5	.053	.053	.065	14,300	24,500
8	.056		.031	22,400	9,900
Bay	.018		.072	7,500	46,800

within the upper range for those reported in other estuaries (Table 7). Oxygen diffusion and gypsum dissolution rates which are largely a function of turbulent horizontal currents (Edwards and Owens, 1964) were at or below rates measured under normal conditions in the Bay. The calculation from the suspended load that from ~0.3 cm of sediment had been disrupted do not appear to be extreme in comparison to sediment activity reported in other studies (Oviatt and Nixon, 1975; McCall, 1977). It appears that a moderate storm mixing condition was simulated.

Storm effects. The storm had no long term effects on suspended load, light extinction, trace metal concentrations, metabolism, nutrient concentrations, phytoplankton, or zooplankton. When suspended loads were highest there were increases in metals, slight increases in nutrients, and decreases in dissolved oxygen. These

Table 7. Suspended particulate loads in some estuaries.

	Dry weight, mg/l
Narragansett Bay, Providence River Maximum	96
Baywide mean (Morton, 1972)	4
Long Island Sound, summer resuspension (for 14m water column, from McCall's (1977) May to Oct mean value of 250.5 mg/cm²/day)	179
Delaware Bay, Surface, Upper Bay (Klemas *et al.*, 1974)	40-120
Upper Chesapeake Bay bottom, low river flow	20-280
surface, high river flow (Schubel, 1972)	20-140
Hurricane Agnes 1972 (Hayes, 1978)	10,000
Storm simulation (this study)	100-270

levels returned to pre-storm levels rapidly, although the decrease in dissolved oxygen was still evident the day after the simulation. Benthic respiration, ammonia release and manganese release were not substantially different after the storm. In tank 6 the storm may have hastened the crash of a phytoplankton bloom through turbulence induced aggregation of organic particulates which through their larger size would sink more rapidly (Santschi *et al.,* 1980). But most of the decrease in the bloom occurred from one to five days after the storm. Chlorophyll concentrations decreased by 37% from 7/15 to 7/17 in tank 6 and by 93% from 7/25 to 8/1. Chlorophyll concentrations in tanks 3 and 4 increased slightly in the week following the storm suggesting that the storm was not necessarily responsible for the continued decline in tank 6.

Dissolved metals. We have not had opportunity to study the effects of storms in Narragansett Bay. However, on two occasions we have obtained Bay samples from the MERL feed water during and after wind storms. In both cases dissolved Fe, Mn, Cu and Cd increased during the event and declined rapidly afterwards similarly to the simulated storm (Hunt, unpublished data). The significance of storm induced transport of metals within and from an estuary cannot be quantified by the simulated storm; it did demonstrate that metal concentrations could be elevated by sediment erosion.

The source of the dissolved Mn is assumed to be the surface pore water. Calculations of the pore water Mn concentrations necessary to cause the observed elevation in dissolved Mn in the tank (Table 3) are consistent with Mn concentrations in the pore waters for the surface 1 cm of similar sediments from Narragansett Bay of 30-50 μM (Elderfield *et al.,* 1981a). The suggestion is that increased dissolved Mn concentrations in the water column resulted from the release of pore waters during sediment disruption. Calculations of pore water Fe and Cu concentrations also suggest the increases of these dissolved metals in the water column were probably caused by mechanical release of the pore waters.

Nutrients. Generally nutrients increased slightly during storm but it does not appear that they came from the eroded pore water as the metals did. An estimate of the potential water column increase from mechanical release of nutrients from the pore waters was made assuming the surface sediment was 70% water by volume and using pore water concentrations in the surface ~0.2-0.3 cm of 25 μg at NH_3-N/1, 5 μg at PO_4-P/1 and 50 μg at Si/1 (Pilson *et al.,* 1981). The calculated increases were generally an order of magnitude less for N and Si and two orders of magnitude less for P than the observed increases (Table 8). If the surface pore water were flushed to a depth of 1 cm, assuming the sediment was 70% water by volume and assuming concentrations in the top centimeter of 100 μg at NH_3-N/1, 20 μg at PO_4-P/1 and 200 μg-at Si/1 (Pilson *et al.,* 1981), the calculated increases would still not explain the observed elevations (Table 8).

Table 8. Observed nutrient changes in the water column and calculated concentrations changes from sediment pore water and benthic remineralization rates.

	Observed changes 7/25-7/26 (28 hr)			μg at/l Calculated from sediment pore water		Calculated from benthic flux mean of rates from 7/17 and 7/27
	Tank 3	Tank 4	Tank 6	~0.2-0.3 cm depth	1.00 cm depth	Tank 4 (28 hr)
Particulate P	—	+0.28	—	+0.290	—	
Ammonia N	+0.32	+0.15	+0.02	+0.013	+0.079	+1.000
Dissolved Inorganic P	+0.15	+0.10	+0.19	+0.003	+0.017	+0.062
Dissolved Si	+0.94	+0.34	N.D.	+0.025	+0.158	+1.842

N.D. not detectable

Table 9. Comparison of the daily flux of NH_4, PO_4 and Mn from the sediments of Narragansett Bay during the summer with estimated releases from sediment pore water during a storm sufficient to resuspend 1 and 5 cm of sediment. Results are based on an area of 272 km^2 and porosity of 72 and 69 for the 0-1 and 0-5 cm sections, Pilson *et al.*, 1981.

Element	Depth interval cm	Pore water concentration μm	Release per storm moles storm^{-1} bay^{-1}	Benthic flux (summer) moles m^{-2} d^{-1}	Benthic release per day moles d^{-1} bay^{-1}
NH_4	0-1	100-800[a]	2 to 16 $\times 10^5$	3-12[b]	8 to 33 $\times 10^5$
	0-5	100-800[a]	9 to 75 $\times 10^5$		
PO_4	0-1	100-500[a]	2 to 10 $\times 10^5$	0.2-1.5[c]	0.5 to 4 $\times 10^5$
	0-5	100-500[a]	9 to 47 $\times 10^5$		
Mn	0-1	2-36[a]	0.04 to 0.7 $\times 10^5$	0.4-0.6[d]	1 to 1.6 $\times 10^5$
	0-5	2-15[a]	0.2 to 1.4 $\times 10^5$		

a. Elderfield *et al.*, 1981a.
b. Nixon *et al.*, 1976; Pilson *et al.*, 1981; Elderfield *et al.*, 1981b.
c. Nixon *et al.*, 1980b; Elderfield *et al.*, 1981b.
d. Graham *et al.*, 1976; Hunt, 1981; Elderfield *et al.*, 1981b.

Additionally, the metals would have reflected flushing to greater depths if this were the case. Finally, the observed increases in particulate phosphate were also consistent with this erosion depth of 0.2-0.3 (Table 8). It seems most likely that benthic and water column remineralization (Fig. 7) combined with a decreased photosynthesis during the storm resulted in the slight nutrient increases. Thus a major phytoplankton bloom such as was observed after Hurricane Belle would have to have been dependent on nutrients in run-off or vastly greater erosion of sediments than in this storm simulation.

Natural storms often cause the deposition of 1 to 5 cm of sediment in shallow water (Bokuniewicz and Gordon, 1980; McCall, 1977; McCall, 1978; Aller, 1980; Bokuniewicz, 1980). McCall (1978) cites the 1976 Hurricane Belle as depositing 4.5-5 cm of graded bedding in 13 m water depth, 0.5 cm at 20 m and no storm effects at 27 m. McCall (1977) estimates that 3 storms per winter may occur which deposit 1 cm thick storm layer. Of course, this does not mean from 1 to 5 cm were resuspended from one area; the sediment could have come from 0.1 to 0.3 cm eroded from a large area and deposited in smaller depositional areas. From a storm observed in February 1976 Bohlen *et al.* (1979) found suspended loads increased by a factor of 2 and estimated such storms occurred 1 to 3 times per year. In contrast dredging operations increased near field suspended load to 200 mg/l, a factor of 60 greater than background (Bohlen *et al.*, 1979). In the simulated storm suspended load increased by a factor of 52 (Table 7) and only eroded the sediment to a depth of 0.2-0.3 cm. Even if 1 to 5 cm were resuspended the dissolved element release would only be equivalent to one day of summer benthic flux and probably insufficient to cause a phytoplankton bloom (Table 9). We conclude that neither the simulated storm nor the big storms which occur 1 to 3 times per year cause a significant release of dissolved elements from the sediment pore waters.

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