Limnol. Oceanogr., 45(1), 2000, 145–158

Gypsum dissolution is not a universal integrator of 'water motion'

Elka T. Porter[1], Lawrence P. Sanford, and Steven E. Suttles
Horn Point Laboratory, University of Maryland Center for Environmental Science, P.O. Box 775, Cambridge, Maryland 21613

Abstract

The dissolution of gypsum or plaster of Paris has been widely used as an inexpensive integral measure of 'water motion' in the field and in laboratory tanks for studies of physical–biological interactions. Commonly, gypsum-dissolution rates have been calibrated to steady flow speed or velocity in the laboratory and the calibrations have been applied to dissolution (i.e., mass-transfer) rates in the field or in tanks. We evaluated the gypsum-dissolution technique in a steady-flow, a fluctuating-flow, and a mixed-flow environment by comparing dissolution rate to direct flow measurements with an acoustic Doppler velocimeter. We found that dissolution rates were related to steady flow and to fluctuation intensity in the exclusively steady-flow and fluctuating-flow environments, respectively. The relationships were weak in the mixed-flow environment. Finally, dissolution and thus mass-transfer relationships were different in each flow environment, and the effects of steady flow and fluctuation intensity were not additive. Providing that it is rigorously checked and appropriately calibrated, the dissolution technique can be used to measure steady flow speed or fluctuation intensity in a steady-flow or fluctuating-flow environment, respectively. However, comparisons of dissolution rates between steady-flow, fluctuating-flow, and mixed-flow environments or within environments that change over time to determine water motion will be misleading. The gypsum-dissolution technique can be used as a good direct indicator of mass-transfer rates. However, mass-transfer rates are different in different flow environments. The gypsum-dissolution technique is not a universal integrator of 'water motion.'

The dissolution of gypsum or gypsum-based plaster of Paris from ''plaster balls'' or ''clod cards'' was first introduced by Muus (1968) and Doty (1971) as an inexpensive technique to measure water flow in the absence of expensive field instrumentation for direct measurements of water velocity. Effects of temperature, salinity, and water volume on dissolution rates were subsequently investigated by Jokiel and Morrissey (1993) and Thompson and Glenn (1994). Since its first introduction, the gypsum-dissolution technique has been widely used in many habitats and for many applications, especially for studies of physical–biological interactions (Table 1). The gypsum-dissolution technique has been thought to provide a comparative or absolute measure of water movement that ''incorporates any water motion due to tidal as well as wind-wave effects in the same integrated measure'' (Wildish and Kristmanson 1997). Furthermore, the dissolution technique has expanded to include materials other than gypsum (e.g., Koehl and Alberte 1988; Bartol et al. 1999).

The flow variables addressed using gypsum dissolution are surprisingly diverse and are often very nonspecific, e.g., current velocity, flow intensity, turbulence intensity, or water motion (Table 1, column A). Thus, in many of the studies using gypsum dissolution it is not clear what was measured. In addition, many different calibrations between dissolution rates and these flow variables have been used (Table 1, column B). Commonly, gypsum-dissolution rates have been calibrated to flow speeds in the laboratory (Table 1, column B). These flow-speed calibrations have then been applied to dissolution rates obtained in the field. In addition, a diffusion index factor (DF) (Doty 1971), determined by dividing the weight loss of gypsum exposed to flow in the field by the weight loss of gypsum in still water of the same temperature and salinity, has often been used to compare water flow between different habitats.

Inconsistencies in gypsum-dissolution results compared to water flow have been observed in many studies. Doty (1971) noted that, despite the most careful treatment, results from clod cards held under the same flow conditions were highly variable. In addition, he noted that results obtained from several tidal cycles were difficult to replicate (Doty 1971). Jokiel and Morrissey (1993) cautioned against the use of still-water controls used to obtain a diffusion factor, and Thompson and Glenn (1994) recommended discontinuing the use of still-water controls because of the variability introduced. Nixon et al. (1980) speculated that turbulence may have contributed to dissolution rates in their studies. Santschi et al. (1983), calling the gypsum-dissolution technique ''a poor man's turbulence sensor,'' used it for determination of diffusive boundary-layer thickness. Pettricrew and Kalff (1991) also suggested that gypsum dissolution may be a quantitative and qualitative turbulence sensor in marine and freshwater systems, though they calibrated gypsum-dissolution rates to steady flow speeds and not to turbulent energy.

[1] Present address: Chesapeake Biological Laboratory, University of Maryland and Center for Environmental Science, P.O. Box 38, Solomons, Maryland 20688.

Acknowledgments

We thank W. Boicourt for letting us participate in the field ''Tower'' experiment and for providing the temperature and salinity data to calibrate the field-dissolution results. We thank K. Sebens, D. Stoecker, V. Kennedy, M. Palmer, and three anonymous reviewers for helpful reviews of earlier versions of this manuscript. Last but not least, we thank J. Seabrease for helping us build the annular flume used and T. Goertemiller for constructing the mesocosms. Our research was supported by grant R 824850-01-0 by the EPA STAR program as part of the Multiscale Experimental Ecosystem Research Center at the University of Maryland Center for Environmental Science, and by a graduate fellowship of the Horn Point Laboratory, UMCES, to E.T.P. We appreciate this support. This is UMCES publication No. 3256.

Table 1. Gypsum-based dissolution technique used to measure a diverse number of water flow variables (column A) for studies of physical–biological–chemical interactions (column D). Gypsum dissolution has been calibrated in various ways (column B) and has been deployed in a multitude of habitats (column C) that may potentially experience different combinations of steady flow and fluctuations. For abbreviation key see columns below table. Italic numbers refer to references listed below: Angradi & Hood (1998)[1], Arsenault et al. (1997)[2], Baird & Atkinson (1997)[3], Buchholtz-ten Brink et al. (1989)[4], Bushek (1988)[5], Crabtree & Trudgill (1984)[6], Cusson & Bourget (1997)[7], Davis et al. (1980)[8], Doty (1971)[9], Eckman et al. (1989)[10], Erftemeijer & Herman (1994)[11], France & Holmquist (1997)[12], Gerard & Mann (1979)[13], Gerard (1982)[14], Glenn & Doty (1992)[15], Goertemiller (1988)[16], Guichard and Bourget (1988)[17]; Howerton & Boyd (1992)[18], Jokiel & Morrissey (1993)[19], Jokiel (1978)[20], Kemper et al. (1975)[21], Komatsu & Kawai (1992)[22], Komatsu & Murakami (1994)[23], Leichter & Witman (1997)[24], Leonard et al. (1998)[25], McGehee (1994)[26], Merrell (1996)[27], Molloy & Bolton (1996)[28], Mullineaux & Butman (1990)[29], Muus (1968)[30], Navas (1990)[31], Newsome & Aalto (1987)[32], Nixon et al. (1980)[33], Opdyke et al. (1987)[34], Petticrew & Kalff (1991)[35], Porter (1999)[36], Porter et al. (this study)[37], Sanford et al. (1994)[38], Sanford et al. (in prep.)[39], Santschi et al. (1983)[40], Santschi et al. (1991)[41], Thompson & Glenn (1994)[42], West (1997)[43], Yamahira (1997)[44].

A Flow variable	B Calibration variable*	C Deployment environment†	D Study objective‡
Water motion	**(DF)** *5, 9, 11, 16, 42*; **(DF-fs)** *5, 14, 19, 20, 23*; **(fs-f)** *19, 30, 44*; **(fs-r)** *15, 42*; **(m)** *16, 26, 28, 42, 43*;	**(aw)** *19*; **(c)** *15, 26, 43*; **(k_b)** *9, 26*; **(m)** *20, 42*; **(mb)** *14*; **(r)** 5, *19, 26*; **(ms)** *9, 11, 14, 19, 23, 28*; **(se)** *14, 15, 28*; **(ss)** *9, 16, 19, 23, 30, 42*; **(w)** *5, 19, 42*	**(ad)** *16, 19, 23, 26, 30, 42*; **(bf)** *23*; **(d)** *9, 15, 20*; **(fc)** *19*; **(g)** *15, 20*; **(mor)** *28, 43*; **(p)** *5*; **(sp)** *16, 26*; **(up)** *11, 14*
Current velocity/Flow speed	**(fs-f)** *22, 23, 37, 35*; **(fs-o)** *6*, 21; **(fs-r)** 1, 2; **(m)** *7, 17, 32*; **(fs-s)** *2, 23, 31, 35*	**(ad)** *32*; **(b)** *1, 6*; **(c)** *2*; **(m)** *37*; **(ms)** *23*; **(r)** *17*; **(ss)** *2, 32, 7*; *37, 23*; **(w)** *37*	**(ad)** *23, 31, 32, 37*; **(bf)** *23*; **(cal)** *35*; **(i)** *1*, **(p)** *2*; **(sp)** *7, 17*
Waves	**(DF)** *16, 28*; **(m)** *16, 44*	**(aw)** *44*; **(ms)** *28*; **(se)** *28*; **(ss)** *16, 44*	**(ad)** *44, 16*; **(mor)** *28*; **(sp)** *16*;
Flow intensity/Flow energy	**(DF)** *13*; **(fs-f)** *27*; **(fs-r)** *2*; **(m)** *7, 26, 27*	**(ad)** *27*; **(c)** *2, 26*; **(k_b)** *7, 26*; **(m)** *27*; **(r)** *26*; **(se)** *13*; **(ss)** *2, 7*	**(ad)** *26*; **(g)** *7, 13, 27*; **(mor)** *13*; **(p)** *2*; **(sp)** *7, 26, 27*; **(up)** *13, 27*
Bulk fluid flux/Gross water movement	**(DF)** *18*; **(fs-r)** *18*; **(m)** *24, 25, 38*	**(c)** *24*; **(m)** *18*; **(ms)** *24*; **(r)** *24*; **(se)** *24, 25, 38*; **(ss)** *24*; **(k_b)** *38*	**(ad)** *18*; **(g)** *38*; **(p)** *24*; **(sp)** *24, 25, 38*
Turbulence intensity	**(DF)** *11*; **(m)** *12*; **(q)** *36, 39, 37*	**(aw)** *36, 37, 39*; **(m)** *36, 37, 39*; **(ms)** *3, 11, 12*; **(ss)** *36, 39*; **(w)** *36, 37, 39*	**(ad)** *36, 37, 39*; **(cal)** *36, 37, 39*; **(up)** *11, 12*
Shear stress	**(τ_b)** *4, 34, 41*	**(fl)** *4, 34*; **(m)** *4, 34, 41*	**(ad)** *34, 41*; **(cal)** *3*; **(d)** *4, 34, 41*
Energy dissipation rate	**(m)** *33*	**(aw)** *33*; **(m)** *33*; **(ss)** *33*; **(w)** *33*	**(ad)** *33*; **(cal)** *33*
Mass transfer	**(m)** *3, 10*; **(τ_b)** *4, 41*; **(z)** *40*	**(fl)** *4, 40*; **(m)** *4, 41*; **(ms)** *10*; **(ss)** *3*	**(ad)** *41*; **(cal)** *4*; **(d)** *3, 4, 10, 40, 41*
Spatial pattern of dissolution	**(m)** *29*	**(ss)** *29*	**(sp)** *29*

* **(DF)** DF (Diss. rate vs still water 'control'); **(DF-fs)** DF versus flow speed; **(fs-f)** Diss. rate vs flow speed (in flume, circuit tank); **(fs-o)** Diss. rate vs flow speed (cylinder, flow chamber); **(fs-r)** Diss. rate vs flow speed (in rotating arm tank); **(fs-s)** Diss. rate vs flow speed in situ (current meter); **(τb)** Shear stress; **(m)** None (mass loss per time); **(q)** Diss. rate vs turbulence intensity *1*; **(z)** Film thickness.

† **(aw)** Close to air-water interface; **(b)** Belowground; **(c)** Inside of or directly near a cage/rack; **(fl)** Flush with solid surface; **(k_b)** Close to smaller roughness elements; **(m)** Mesocosm/pond; **(mb)** Attached to macrophyte blades; **(ms)** In- and/or outside macrophyte/seagrass/marsh beds; **(r)** Around reefs/boulders/pier pilings; **(se)** In sheltered vs exposed fluid habitat; **(ss)** Close to or at solid surface; **(w)** Suspended in water column.

‡ **(ad)** Compare flow over different areas or depths; **(bf)** Effect of biology on flow; **(cal)** Calibrate device for desired flow parameters; **(d)** Effect of flow on diffusion/mass transfer enhancement; **(g)** Effect of flow on plant/animal growth; **(fc)** Interaction of flow and coral coverage; **(i)** Measure interstitial water velocity; **(mor)** Effect of flow on plant/animal morphology; **(p)** Effect of flow on particle transport & animal growth; **(sp)** Effect of flow on community composition or species distributions; **(up)** Effect of flow on nutrient uptake.

Gerard (1982) used gypsum buttons calibrated in a flume to calculate flows in a dense macrophyte forest. She estimated flow speeds of about 4 cm s^{-1} with this technique, even though the in situ flow speeds had appeared much lower to her, on the order of 1 cm s^{-1}. Komatsu and Murakami (1994) measured flow speeds of 1.6 cm s^{-1} with a current meter, whereas flow-speed estimates using gypsum-dissolution techniques at the same location in a macrophyte forest were much higher at 5.7 cm s^{-1}.

Mass transfer of gypsum to the water is controlled by the thickness of the diffusive boundary layer around the gypsum objects and the concentration gradient across the diffusive boundary layer (Barton and Wilde 1971; Liu and Nancollas 1971; James and Lupton 1978; Opdyke et al. 1987). The diffusive boundary layer is a bottleneck for the transfer of solutes and gases because the transfer is controlled by molecular diffusion in the diffusive boundary layer. If it is assumed that the Ca^{2+} concentration is saturated at the gypsum sphere and near zero in the surrounding environment and that Ca^{2+} is transported away from the sphere, then the thickness of the diffusive boundary layer is the only controlling factor for gypsum dissolution, i.e., for mass transfer. A thinner diffusive boundary layer leads to an increased rate of gypsum loss to the surrounding water, and thus to an enhanced dissolution rate.

Both steady flow speed and fluctuation intensity can affect the thickness of the diffusive boundary layer and can thus affect the dissolution rate of gypsum. An increase in steady flow speed past a stationary object can decrease the diffusive sublayer thickness and enhance mass transfer (James and Lupton 1978), and can thus increase gypsum-dissolution rate. Equivalently, an increase in the speed of the object through water can decrease the thickness of the diffusive boundary layer, as has also been discussed in the context of sinking aggregates (Csanady 1986; Lazier and Mann 1989). Methods commonly used to calibrate gypsum-dissolution objects have subjected gypsum objects to a steady flow in flumes (Table 1, column B, fs-f, fs-o) or moved them at a steady rate through water (Table 1, column B, fs-r) which decreases the thickness of the diffusive boundary layer.

Alternatively, fluctuations in the flow can decrease the diffusive sublayer's thickness and increase mass transfer (Jaehne et al. 1987; Sanford 1997) with or without an accompanying steady flow. Fluctuations in the flow can be generated by waves, oscillating flow, and small-scale turbulence such as from eddies or wakes around roughness elements or in aggregations. Several studies have pointed out the connection of fluctuations in the flow and mass transfer as mediated by changes in the diffusive boundary-layer thickness. For example, Stevens and Hurd (1997) suggested, based on a modeling study using published data, that waves may decrease diffusive boundary-layer thickness, thereby enhancing nutrient uptake by a macrophyte. Jaeger (1998) and Nishimura et al. (1998) found that an increase in oscillation frequency in oscillatory flow can increase mass transfer. Gundersen et al. (1992) found that fluctuations in flow, though not as regular, significantly decreased diffusive boundary-layer thickness and could increase the nutrient and oxygen supply to a hydrothermal vent bacteria mat. Carpenter and Williams (1993) found that oscillatory flow enhanced reef algal turf photosynthesis by 20% over unidirectional flow and suggested that turbulence resulting from the reversal of flow direction disrupted the diffusive boundary layers.

Importantly, the mass-transfer (dissolution) rate may differ depending on the relative strengths of steady flow speed and fluctuation intensity in the flows to which gypsum objects are exposed. Flow environments may be defined in one sense by the ratio of steady flow speed to fluctuation intensity. Terray et al. (1996) operationally defined fluctuation-dominated flows as those in which the ratio of steady flow speed to fluctuation intensity is smaller than 1. Conversely, flow environments that have a large component of steady flow relative to fluctuation intensity can be termed steady-flow dominated. Flow environments that have almost equal components of steady and fluctuating flow can be termed mixed-flow environments. The interaction of flow with biological structures such as corals, seagrasses, marsh plants, or macrophytes can increase fluctuation intensity relative to steady flow speed and can change a steady-flow dominated environment to a mixed flow or fluctuation-dominated flow (Table 2).

Studies that have measured both steady flow speed and fluctuation intensity in natural environments indicate that dense marshes, macrophyte or seagrass beds, and locations near rocks represent mixed or fluctuation-dominated flow environments (Table 2). Similarly, locations near cages or meshes that enclose gypsum-dissolution objects to protect them from being disturbed can be mixed or fluctuation-dominated environments. Experimental ecosystems stirred by oscillating paddles (this study; Sanford et al. in prep.; Porter 1999) or mixed using grids (Howarth et al. 1993; Landry et al. 1995) can be dominated by fluctuating flow with near zero steady flow speeds. Wave action is an additional source of fluctuating flow that is unrelated to the steady flow and can produce fluctuation, mixed-flow dominated, or variable environments (Table 2). Water columns away from solid or moving boundaries in tidal channels and away from dense aggregations tend to be dominated by steady flow (Table 2).

The objective of this paper is to examine whether gypsum-dissolution rates can indeed be used as an integral measure of 'water motion' for both steady flows and fluctuating flows. We examined the relationships of gypsum-dissolution rates to steady flow speed, fluctuation intensity, and flow intensity, respectively, in three different laboratory flow environments. We also provide an example of measurements in one field environment. First, we describe the dissolution techniques, calibrations, and the definitions of flow environment used for our dissolution experiments. We then compare the relationships between dissolution rate and steady flow speed and fluctuating flow in these different environments. A series of rigorous checks is suggested that should be followed if the gypsum-dissolution technique is to be used to determine 'water motion' in natural environments or experimental ecosystems. Finally, we discuss our results in light of published studies that have used dissolution techniques for interdisciplinary research.

Materials and methods

For the preparation of gypsum spheres we followed techniques by Muus (1968), Doty (1971), and Jokiel and Mor-

Table 2. Examples of direct measurements of steady flow speeds (u_{steady}) and fluctuation intensity (q) in natural habitats and the type of flow environment in the respective habitats. For comparability, the values of q in these studies have been converted to the definition of q by Tennekes & Lumley (1972) used in this study. SF = steady-flow environment ($u_{steady}/q > 9$); MIX = mixed-flow environment ($1 < u_{steady}/q < 4$); FF = fluctuating − flow environment ($u_{steady}/q < 1$); MIX-SF transition = transition between mixed flow and steady flow environment ($4 < u_{steady}/q < 9$). BBL = benthic boundary layer.

Location	Reference	Measured u_{steady} (cm s^{-1})	Measured q (cm s^{-1})	Ratio u_{steady}/q	Flow environment
Edge of macrophyte bed, current swept, ~1 h after slack tide	Koehl & Alberte 1988	33	6.93	4.8	MIX-SF transition
Middle of macrophyte bed, current swept, ~1 h after slack tide	Koehl & Alberte 1988	22	6.38	3.4	MIX
Middle of macrophyte bed, current swept site, slack tide	Koehl & Alberte 1988	0.4	4.26	0.09	FF
Protected site, peak tidal current	Koehl & Alberte 1988	36	7.92	4.5	MIX-SF transition
Barren marsh (*S. alterniflora*)	Leonard & Luther 1995	9.15	8.78	1	FF
Vegetated marsh (*S. alterniflora*, 128/234 stems m^{-2})	Leonard & Luther 1995	5.19/2.81	2.01/0.77	2.6/3.6	MIX/MIX
Seagrass bed (*Z. marina*), 7 cm (400/1,200 shoots m^{-2})	Gambi et al. 1990	5	1.25/2	4/2.5	MIX/MIX
Seagrass bed (*Z. marina*), 7 cm (400/1,200 shoots m^{-2})	Gambi et al. 1990	10	2.5/5	4/2	MIX/MIX
Seagrass bed (*Z. marina*), 7 cm (400/1,200 shoots m^{-2})	Gambi et al. 1990	20	4/10	5/2	MIX-SF transit./MIX
Above stones (2 mm)	Hart et al. 1996	24.6	7.2	3.4	MIX
Front/Wake of boulder (measured 12 cm above bottom)	Bouckaert & Davis 1998	37.2/10.2	1.47/1.9	25.29/5.4	SF/MIX-SF transition
Front/Wake of boulder (measured 2.5 cm above bottom)	Bouckaert & Davis 1998	5.5/5.7	1.4/1.9	3.9/3	MIX/MIX
Front/Wake of boulder (measured 0.6 cm above bottom)	Bouckaert & Davis 1998	12.0/4.4	1.2/1.4	10/3.1	SF/MIX
Open water (Water off Anglesey, North Wales)	Bowden 1962	50	4.85	10.3	SF
Open water (Estuary, Choptank River, Maryland)	Gordon and Dohne 1973	52.6	3.42	15.4	SF
Open water (Skagit Bay, Washington)	Gross and Nowell 1983	45.87	4.1	11.2	SF
Open water (Long Island Sound)	Bohlen 1977	40	5	8	SF
High current speed + moderate waves, mid contin. shelf BBL	Gross et al. 1994	10	4.8	1.41–2.8	MIX
High current speed + low waves, mid contin. shelf BBL	Gross et al. 1994	10	3.3	1.41–4.7	MIX
Low current speed + high waves, mid contin. shelf BBL	Gross et al. 1994	5	6.4	0.15–1.41	FF–MIX

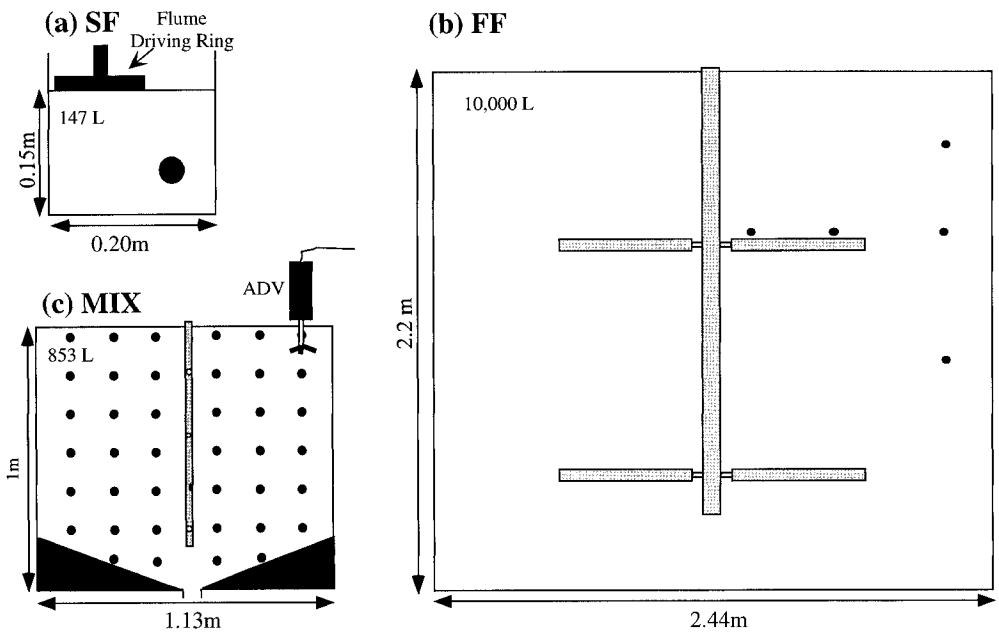

Fig. 1. Gypsum spheres (black circles) in a steady-flow (SF) environment in an annular flume, a fluctuating flow (FF) environment in a tank with oscillating paddles, and in a mixed flow (MIX) environment in which mixing was created by pulsed jet flow directed out of a pipe in the center of the tank. Steady flow speed, fluctuation intensity, and flow intensity were measured at each gypsum sphere location using an acoustic Doppler velocimeter (ADV) over a range device specific of flow settings in each device.

issey (1993). We prepared 3-cm diameter gypsum spheres by mixing plaster of Paris (ca. 80% $CaSO_4 \cdot H_20$, ca. 20% $CaCO_3$, DAC Inc., Dayton, Ohio) with deionized water in a ratio of 2 : 1 (v : v) and gently stirred the mix until it had a soft consistency without air bubbles. By syringe, we filled 3-cm diameter spherical ice cube molds which had 7.62-cm long bolts inserted through holes so as to be screwed into our suspension structures. In addition, we prepared 5-cm diameter spheres in racquet ball molds to be used for a field-dissolution experiment because an initial set of 3-cm gypsum spheres were eroded beyond their linear range. After ≥30 min of setting time, the spheres were removed from the mold and any unevenness scraped off. They were then numbered using small tags attached to the bolt and dried to constant weight at 65°C for ≥24 h. Immediately after drying, the weight of the spheres was recorded to 0.01 g. After deployment of gypsum spheres and slow and careful retrieval at the end of each experimental run, the gypsum spheres were redried and reweighed, and the gypsum loss per hour, i.e., the dissolution rate, was determined. Dissolution rates were temperature corrected to a mean temperature of 20°C as determined from fig. 3 in Jokiel and Morrissey (1993). All experiments were run at a salinity between 10 and 15‰ in the laboratory, and salinity effects should be negligible (Jokiel and Morrissey 1993). The mean temperature in all laboratory experiments was 20°C, and only small temperature corrections were necessary. In all laboratory experiments, we obtained temperature-corrected dissolution rates of the 3-cm spheres from about 0.04 to about 0.42 g h^{-1}.

We produced three different flow environments for our laboratory experiments (Fig. 1). For a very steady-flow dominated environment, we used an annular flume with a half lid. The annular flume had a 1.80-m outer diameter, a 20-cm wide channel, 15-cm water column height (Fig. 1a), and low secondary circulation (Porter 1999). For a fluctuation-dominated environment, we used a 2.44-m diameter, 2.2-m high, cylindrical, 10,000-liter volume mesocosm (Fig. 1b) that was uniformly mixed by sets of impellers on shafts that extended vertically into the center of the tank. The impellers were driven by separate overhead motors and swept the inner half diameter of the tank. The impeller blades of the tank were located 52.8 and 162 cm from the water surface, were 8-cm wide, and were tilted at a 45° angle to the surface. To prevent plug flow, the impellers were programmed to rotate in one direction for 2.25 revolutions, stop for 15 s, and then rotate in the opposite direction for 2.25 revolutions. For a mixed-flow dominated and more variable flow environment, we used a 870-liter volume cylindrical mesocosm of 1.13-m diameter with a funnel-shaped bottom; it was mixed by pulsed jet flow entering through a perforated pipe in the center of the tank (Fig. 1c). The pulsed jet flow was produced by an air-lift pump forcing 4.3 to 5.6 pulses per minute of 2.6-liter water per pulse into the tank.

Our three different flow environments of steady flow, fluctuating flow, and mixed flow were defined by their ratios of steady flow speed (u_{steady}) to fluctuation intensity (q) (Fig. 2). A log–log plot of the ratio of steady flow speed (Eq. 1 below) to fluctuation intensity (Eq. 2 below) versus dissolution rate clearly separates flows that were steady-flow dominated ($u_{steady}/q > 9$), fluctuating-flow dominated ($u_{steady}/q < 1$, Terray et al. 1996), and mixed-flow dominated ($1 < u_{steady}/q < 4$) (Fig. 2).

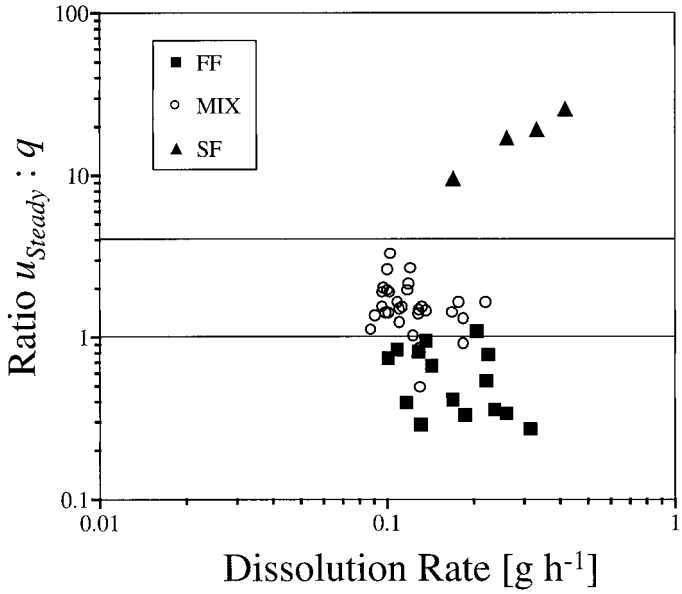

Fig. 2. Ratio of steady flow speed (u_{steady}) to fluctuation intensity (q) versus dissolution rate allows a separation between flow environments. Ratios obtained for the field experiment ranged from about 5 to 7. FF = fluctuating-flow environment (n = 15), MIX = mixed-flow environment (n = 33), SF = steady-flow environment (n = 4). Any data points with a dissolution rate below 0.07 g h^{-1} were discarded.

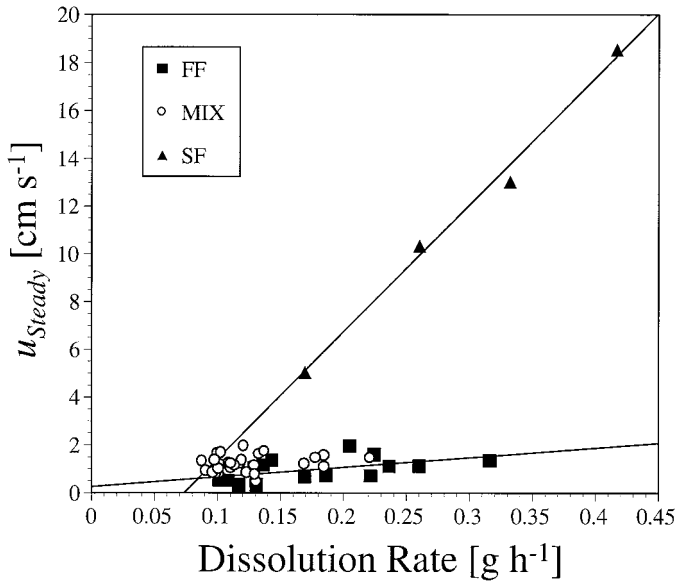

Fig. 3. Steady flow speed (u_{steady}) versus gypsum-dissolution rate of 3-cm spheres in three flow environments. FF = fluctuating-flow environment (n = 15), MIX = mixed-flow environment (n = 33), SF = steady-flow environment (n = 4). Any data points with a dissolution rate below 0.07 g h^{-1} were discarded.

For all dissolution experiments, we (1) deployed gypsum spheres at one location in the annular flume and at various distances from paddles or jets in the tanks with minimum distances of at least four sphere lengths between spheres, (2) kept the spheres from agitating, (3) limited the number of spheres deployed at any one time to minimize turbulence created by the spheres themselves, (4) used large volumes of water and exchanged water between runs to avoid Ca^{2+} saturation, and (5) ensured that each sphere had a measurable total weight loss, although of less than 70% of its total weight, to achieve an approximately linear weight loss over time (Jokiel and Morrissey 1993). Dissolution experiments were conducted for 24 to 46 h, and the length of an experiment in the laboratory was based on visually inspecting the size of the gypsum spheres.

At each gypsum sphere location but without spheres present, flow was measured directly using an acoustic Doppler velocimeter (ADV, SonTek Inc., San Diego, California) (Kraus et al. 1994; George 1996) at a sampling rate of 25 Hz over ≥15-min duration in the tanks and 1-min duration in the annular flume. Steady flow speeds (u_{steady}) were calculated using

$$u_{steady} = \sqrt{(U^2 + V^2 + W^2)}, \tag{1}$$

where U, V, W are the average velocities in the three directions (U in the annular flume was oriented along the primary flow axis). Equation 1 is the standard definition of steady flow speed in physical studies, there termed ''mean flow speed.'' Gypsum spheres commonly have been calibrated to steady flow speeds in flumes or rotating tank devices (Table 1). Different definitions of fluctuation intensity have been used in the literature, and we defined fluctuation intensity in the same manner as turbulence intensity ($q = u_{RMS}$) is defined by Tennekes and Lumley (1972):

$$q = \sqrt{\frac{1}{3}(\langle u^2\rangle + \langle v^2\rangle + \langle w^2\rangle)}, \tag{2}$$

where $\langle u^2\rangle$, $\langle v^2\rangle$, and $\langle w^2\rangle$ are the variance of their respective velocity components. In addition, we calculated a flow intensity that includes both steady flow speed and the fluctuations in flow in a single flow measure and that may represent the total 'water motion' best. Flow intensity ($u_{RMS,total}$) was calculated as the total root mean square velocity where the mean has not been removed, unlike in Eq. 2

$$u_{RMS,total} = \sqrt{\frac{1}{3}\left[\langle (U + u)^2\rangle + \langle (V + v)^2\rangle + \langle (W + w)^2\rangle\right]}. \tag{3}$$

Steady flow speeds, fluctuation intensity, and flow intensity, respectively, were each compared to gypsum-dissolution rates at each gypsum sphere location in the different flow environments. Regression analyses were performed for steady flow, fluctuation intensity, and flow intensity versus dissolution rate using SAS® 6.0 (SAS Institute Inc., Carey, North Carolina).

In our experiments we discarded any dissolution rates below 0.07 g h^{-1}, where the regression lines from steady flow speed and fluctuation intensity intercepted the x axis in the steady- and fluctuating-flow environments, respectively

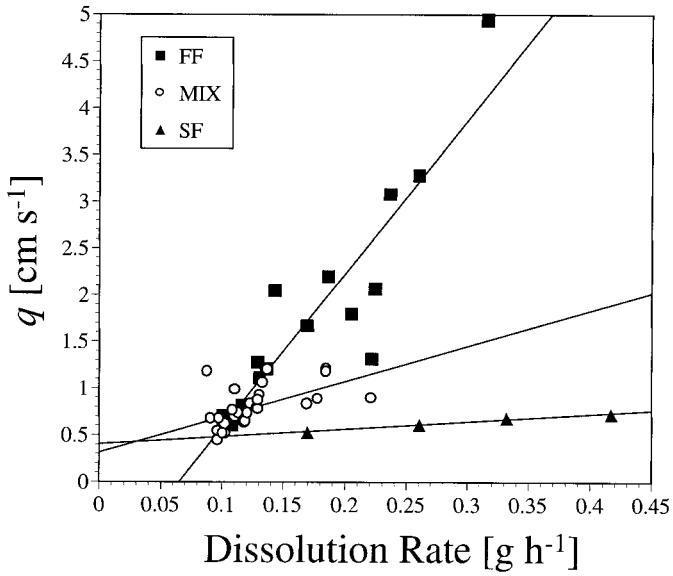

Fig. 4. Fluctuation intensity (q) versus gypsum-dissolution rate of 3-cm spheres in three flow environments. FF = fluctuating-flow environment (n = 15), MIX = mixed-flow environment (n = 33), SF = steady-flow environment (n = 4). Any data points with a dissolution rate below 0.07 g h^{-1} were discarded.

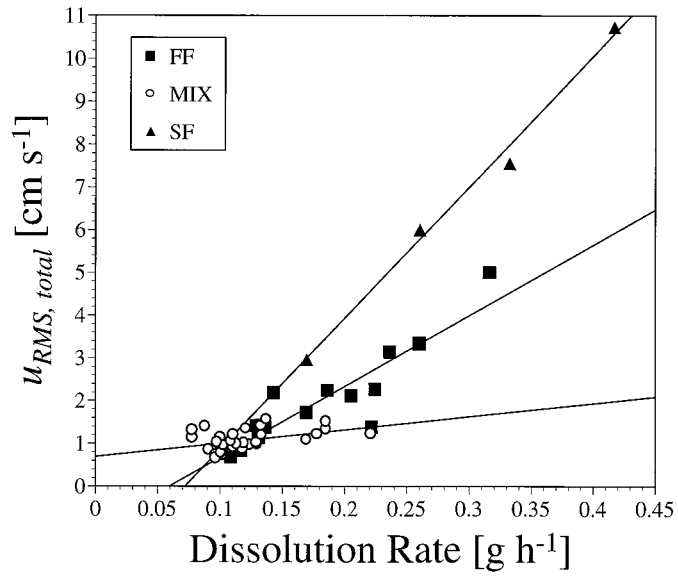

Fig. 5. Flow intensity ($u_{\mathrm{RMS,\ total}}$) versus gypsum-dissolution rate of 3-cm spheres in three flow environments. FF = fluctuating-flow environment (n = 15), MIX = mixed-flow environment (n = 33), SF = steady-flow environment (n = 4). Any data points with a dissolution rate below 0.07 g h^{-1} were discarded.

(Figs. 3–5). Gypsum-dissolution rates smaller than 0.07 g h^{-1} would have been equivalent to negative steady flow speeds, fluctuation intensities, and flow intensities. At such small dissolution rates, gypsum-dissolution rate may be affected by factors beyond experimental control.

To provide an example of how misleading it can be to use steady flow speed laboratory-calibrated dissolution rates to determine flow speeds in the field, as is frequently done (e.g., Komatsu and Murakami 1994; Arsenault et al. 1997; Bartol et al. 1999), we compared dissolution rates to steady flow speeds in a natural flow environment directly. We performed a field-dissolution experiment at a fixed tower station at 28°29.6′N, 76°22.3′W in Chesapeake Bay, 1.5 m below mean water level. Northern Chesapeake Bay is characterized by three second-period waves (Lin et al. 1997), and fluctuations due to waves as well as turbulence can be determined using Eq. 2, allowing us to characterize the flow environment using the ratio of steady flow speed to fluctuation intensity. Initially we deployed 3-cm spheres, but they dissolved too rapidly, so we used 5-cm spheres for the field experiments. In three experiments within the same week we deployed three 5-cm gypsum spheres each within 50-cm horizontal distance of an upward-looking SonTek Hydra ADV (SonTek). Pressure, u, v, and w were burst sampled twice an hour for 7.5 min per sample at a sampling rate of 4 Hz. Time series of steady flow speeds and fluctuation intensities were calculated using Eqs. 1 and 2, respectively. In addition, the ratio of steady flow speed to fluctuation intensity was calculated to determine the type of flow environment the gypsum spheres were exposed to throughout the field experiments. Steady flow speeds, fluctuation intensities, and the mean ratio of steady flow speed to fluctuation intensity were determined for the duration of the gypsum-dissolution experiments. In every experiment, we ensured that at least 30% of the sphere's total weight was left upon retrieval, as recommended by Jokiel and Morrissey (1993).

To correct the field-dissolution rates for temperature and salinity, we used temperature and salinity measurements collected 2.4 m below the surface at a buoy station ca. 50 m from the field-dissolution experiment. Temperatures in the field were about 27°C, which made large temperature corrections to 20°C necessary. Field-dissolution rates were salinity corrected to the mean salinity of 10‰ and temperature corrected to 20°C as determined from figs. 4 and 3, respectively, in Jokiel and Morrissey (1993). In all field experiments, we obtained temperature- and salinity-corrected dissolution rates of the 5-cm spheres of about 0.74 to 1.08 g h^{-1}.

To correct for dissolution rate due to the larger sphere size (5 cm vs. 3 cm) used in the field as mediated by steady flow, we initially adapted theoretical mass-transfer relationships for nutrient uptake in phytoplankton (Pasciak and Gavis 1974) for gypsum-dissolution rates. We used these relationships to convert dissolution rates obtained from 3-cm spheres to dissolution rates obtained from 5-cm spheres in a steady-flow environment. The mass-transfer rate, β, at which gypsum is lost from the sphere is related to (Pasciak and Gavis 1974)

$$\beta = hA(C - C_R), \tag{4}$$

where C and C_R are the gypsum concentrations at the outer and inner side of the diffusive boundary layer, respectively; h is the mass-transfer coefficient; and A is the wetted surface area. Under the present conditions, the mass-transfer rate of the large sphere, β_l, is approximately

$$\beta_l \approx \frac{A_l}{A_s}\beta_s, \tag{5}$$

Table 3. (A, B) Five of the six relationships between dissolution rate and steady flow speed and fluctuation intensity were significant ($p < 0.05$) at the 95% level, although the R^2 was low in two of the significant relationships. The slopes of dissolution rate versus steady flow speed and fluctuation intensity, respectively, were significantly different between the steady and fluctuating-flow environments. Steady flow speed affected dissolution rate most strongly in the steady-flow environment, followed by the effect of fluctuation intensity on dissolution rate in the fluctuating-flow environment, respectively. (C) The slopes of dissolution rate and flow intensity, which includes both steady flow speed and the fluctuations in flow in a single 'water motion' measure, were significantly different between steady-flow, fluctuating-flow, and mixed-flow environments, and the results were not additive. SF = steady-flow environment ($n = 4$), FF = fluctuating-flow environment ($n = 15$), MIX = mixed-flow environment ($n = 33$).

Dissolution rate (x axis) versus	Flow environment	Slope	Error of slope	Intercept	R^2
A. Steady-flow speed (y axis)†	SF*	53.29	3.38		0.992
	FF*	4.03	1.75	0.23	0.209
	MIX	2.59	1.93	0.85	0.061
B. Fluctuation intensity (y axis)‡	SF*	0.80	0.08	0.40	0.979
	FF*	16.49	2.22		0.810
	MIX*	3.79	1.04	0.31	0.321
C. Flow intensity (y axis)§	SF*	37.06	5.92		0.927
	FF*	16.58	2.16		0.82
	MIX*	3.11	1.15	0.68	0.192

* Significant at the 95% level ($p < 0.05$).
† Defined as in Eq. 1.
‡ Defined as in Eq. 2.
§ Defined as in Eq. 3.

where l and s represent the large and small sphere size. We initially applied Eq. 5 to dissolution rates for small spheres obtained at four steady flow speeds in the steady-flow annular flume. Unfortunately, β_l was unreasonably large using this procedure. We thus experimentally determined the dissolution rates of the 5-cm spheres in the annular flume at three of the four flow speeds used to calibrate the 3-cm spheres. This produced a linear relationship of steady flow speed to dissolution rate for the 5-cm spheres. We compared these laboratory calibrations to the field data.

We also calculated a characteristic dimension L'' (Pasternak and Gauvin 1960) for objects of different shapes and sizes:

$$L'' = \frac{\text{Wetted Surface Area}}{\text{Max. Perimeter Perpendicular To Flow}} \tag{6}$$

and related mass-transfer rates following to yield

$$\beta_l \approx \frac{L_l''}{L_s''}\beta_s. \tag{7}$$

We compared β_l from Eq. 7 to our experimentally determined β_l and to the predictions of Eq. 5.

Results

Overall, gypsum-dissolution rate related well to specific flow variables in specific flow environments, but gypsum dissolution was not a universal integrator of 'water motion' (Figs. 3–5, Table 3). This has implications for the interpretation of gypsum-dissolution results from field or mesocosm experiments. For example, the dissolution rate of 3-cm gypsum spheres was strongly and linearly related to steady flow speed in the steady-flow environment of the annular flume (Table 3A, Fig. 3). There was a weaker but statistically significant relationship between steady flow speed and dissolution rate in the fluctuating-flow environment (Table 3A, Fig. 3), but there was no relationship in the mixed-flow environment. Slopes of the relationships between dissolution rate and steady flow speed for steady and fluctuating-flow environments were significantly different from zero and significantly different from each other.

Dissolution rate was linearly related to fluctuation intensity in both the fluctuating-flow and in the steady-flow environments (Table 3B, Fig. 4). The slope of the relationship, however, was significantly larger in the fluctuating-flow environment than in the steady-flow environment (Fig. 4). There was a weak but statistically significant relationship between fluctuation intensity and dissolution rate in the mixed-flow environment (Table 3B, Fig. 4). The slopes of all relationships of dissolution rate and fluctuation intensity were significantly different from zero and from each other.

Dissolution rate was linearly related to flow intensity in all three flow environments (Table 3C, Fig. 5), and the slopes of all relationships of gypsum-dissolution rate and flow intensity were significantly different from zero and from each other. The slope of the relationship of gypsum-dissolution rate to flow intensity was significantly larger in the steady-flow environment than in the fluctuating-flow environment, and the fluctuating-flow slope was significantly larger than the mixed-flow slope. Because flow intensity includes both the steady flow speed and the fluctuations in the flow, this flow measure represents the additive effect of steady flow speed and fluctuations in the flow, and thus represents 'total water motion' best. Significantly different slopes in different flow environments indicated that gypsum dissolution was not a universal measure of 'water motion'.

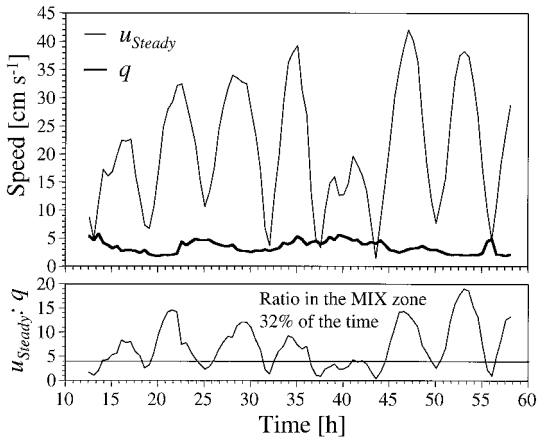

Fig. 6. Steady flow speeds (u_{steady}), fluctuation intensities (q), and the ratio of steady flow speed and fluctuation intensity measured over bursts over several tidal cycles 1.5 m below mean water level in mid-Chesapeake Bay using an acoustic Doppler velocimeter (ADV). The ratio of steady flow speed and fluctuation intensity reaches into the MIX flow environment ($1 < u_{steady}/q < 4$) 32% of the time (bottom panel). Gypsum-dissolution experiments were carried out in parallel in the vicinity of the ADV (see Fig. 7).

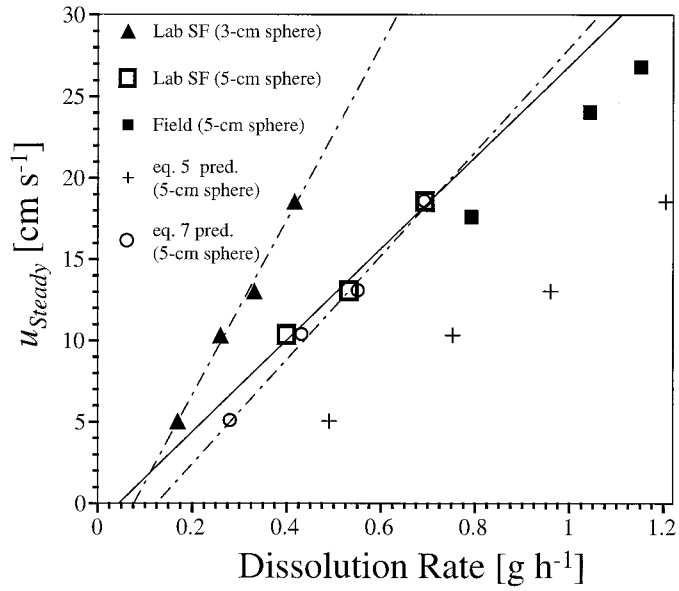

Fig. 7. Calibrations of steady flow speeds versus dissolution rate for 3-cm and for 5-cm spheres in a steady-flow (SF) environment. Theoretical predictions (pred.) of dissolution rates from flow-speed calibrations from Eqs. 5 and 7 (*see text*). Field-dissolution rates were higher than predicted from calibrations of dissolution rate vs. steady flow speed in a flume.

A representative example of the steady flow speeds, fluctuation intensities, and the type of flow environment experienced by the gypsum spheres throughout one of the three field experiments is provided in Fig. 6. Steady flow speeds in the three field-dissolution experiments as calculated over each burst for the period of time of the experiments averaged about 17, 24, and 26 cm s^{-1}, with large regular fluctuations over tidal cycles. Fluctuation intensities averaged 5.2, 4.4, and 3.4 cm s^{-1} over the respective experiments and varied less than steady flow speed over the tidal cycles. In addition, the mean ratio of steady flow speed to fluctuation intensity varied between about 5 and 7 and was slightly lower than the bottom threshold of 9 measured for the laboratory steady-flow environment. However, the ratio of steady flow speed to fluctuation intensity varied greatly over the tidal cycles and reached below 4 into the mixed-flow environment 32, 34, and 25% of the time over the duration of the three runs, respectively.

Dissolution rates from 5-cm spheres calibrated in steady flow in the annular flume increased linearly with flow speed ($u_{steady} = 28.2 \times$ dissolution rate $+ 3.9$ $R^2 = 0.98$) but at a different rate than the 3-cm diameter gypsum spheres (Lab steady flow [SF] 5 vs. 3-cm sphere, Fig. 7). Using Eq. 5 based on the total wetted surface area, we predicted the dissolution rates of the 5-cm spheres to be 2.89 times higher than the dissolution rates of the 3-cm spheres at each flow speed (Eq. 5 predicted, Fig. 7). Using Eq. 7 based on the characteristic dimension index L'' (Pasternak and Gauvin 1960), we predicted the dissolution rates of the 5-cm spheres to be about 1.7 times higher than the dissolution rates of the 3-cm spheres at each flow speed (Eq. 7 predicted, Fig. 7). The laboratory dissolution rates of the 5-cm spheres were also about 1.7 times higher than the dissolution rates of the 3-cm spheres at each flow speed. Gypsum-dissolution rates were 16 to 18% higher in the field than the dissolution rates predicted from the laboratory calibration curve for the 5-cm spheres.

Discussion

The gypsum-dissolution technique has been used for many purposes, often without carefully considering the calibration environment. Inconsistencies in the results from gypsum-dissolution studies have been noted since this technique was first proposed as a method for measuring water motion by Muus (1968) and Doty (1971). Diverse methods of calibrating gypsum-dissolution rates have been developed (Table 1, column B), but the most common approach is to calibrate the dissolution of gypsum objects to steady flow speed (Muus 1968; James and Lupton 1978; Table 1, column B). Using laboratory steady flow speed calibrations by either subjecting gypsum objects to flume flow or by moving them through water in a rotating arm tank, all published studies have found excellent relationships between gypsum-dissolution rate and flow speed (Table 1, column B). From these excellent relationships it has often been assumed that it was steady flow speed or current velocity that was measured in the field (e.g., Petticrew and Kalff 1991; Komatsu and Murakami 1994). Moreover, it has been suggested that gypsum-dissolution rates be calibrated to flow speeds and reported in velocity units (Thompson and Glenn 1994). In addition, Petticrew and Kalff (1991) suggested that the gypsum-dissolution technique could potentially be used as a turbulence sensor; however, they calibrated dissolution rates exclusively to steady flow speed. Other investigations assumed that the gypsum-dissolution technique would not only measure steady flow speed, but also measure additional flows, such

as those due to waves (Goertemiller 1988; Molloy and Bolton 1996; Yamahira 1997). In the broadest sense, the dissolution technique has also been assumed to provide a good general index of integrated water motion or water movement (Table 1, column B; Wildish and Kristmanson 1997).

In our study, we found that the dissolution of gypsum increased with increasing steady flow speed as expected in a steady-flow ($u_{steady}/q > 9$) environment, such as an annular flume. In addition, the gypsum-dissolution rate also greatly increased with increasing fluctuation intensity in a fluctuation-dominated ($u_{steady}/q < 1$) flow environment. However, gypsum-dissolution rates were affected quite differently in the two environments. Problems with the application of the dissolution technique for 'water motion' measurements arise when steady flow speed-calibrated gypsum objects are placed into highly fluctuating or mixed-flow field or laboratory environments or vice versa. This can lead to erroneous interpretations of flow from dissolution rate data. Overall, because gypsum dissolution (i.e., mass transfer) as mediated by diffusive boundary-layer thickness responds differently to steady flow speed and fluctuation intensity, the gypsum-dissolution technique should not be used in one flow environment when it has been calibrated in another.

Further, it is problematic to use the dissolution results to compare flow between environments that are different in character. Complex interactions of biological structures such as seagrasses, coral reefs, bivalve reefs, or rocky shores with flow and wave action can be expected to produce different types of flow environments, although few direct measurements of both steady flow speed and fluctuation intensity are available (Table 2). Flows inside dense aggregations, such as macrophytes, seagrasses, or marshes, can be fluctuating or mixed-flow dominated (Table 2), whereas flows outside dense aggregations frequently are steady-flow dominated (open water, Table 2). Flows near roughness elements or close to boundaries can be more like a mixed-flow environment (stones, boulders, Table 2). Depending on depth, the interaction of currents and wave action can also create fluctuating-flow, mixed-flow, or changing environments (currents + waves, Table 2). Even though steady flow speed calibrations in the laboratory may well relate to steady flow speeds 1 m off the bottom, as, for example, found in a study by Arsenault et al. (1997), application of these calibrations to determine steady flow speeds directly at rough bottoms among dense communities (Arsenault et al. 1997) is problematic. For example, flows near stones and in the front and the wake of large boulders can be mixed-flow dominated (Hart et al. 1996; Bouckaert and Davis 1998, Table 2). In addition, flow around bivalve or coral reefs may similarly be mixed-flow or perhaps fluctuating-flow dominated in places. Often gypsum objects have been enclosed in cages in the field to protect them from potential predation (e.g., McGehee 1994; Arsenault et al. 1997). Or, dissolution objects have been placed near cages (Leichter and Witman 1997), among communities on rock walls (Leichter and Witman 1997), onto rocks of different sizes (Cusson and Bourget 1997), around coral reefs (Jokiel 1978; Jokiel and Morrissey 1993; McGehee 1994), or around oyster reefs (Bartol et al. 1999). All these factors increase roughness and thus increase fluctuation intensity. Overall, comparing flow-speed estimates from gypsum-dissolution measurements in different flow environments will be misleading if the same calibration is used for all measurements.

Many natural flow environments are variable over temporal and spatial scales and thus are not exclusively steady-flow or fluctuating-flow environments, but can be mixed-flow environments as mediated by the interacting effects of tides, waves, density differentials, and biology (Table 2). In mixed-flow environments the dissolution technique appears to be an unreliable integrator of either steady flow speed or of fluctuation intensity. In our three field-dissolution experiments, the ratio of steady flow speed to fluctuation intensity dipped into the zone of the mixed-flow environment for about 30% of the time over the duration of each trial (Fig. 6). Gypsum-dissolution rates in our three field experiments were 16 to 18% higher than the gypsum-dissolution rates expected from our steady flow speed calibration relationship. If we had followed commonly used procedures of determining steady flow speeds from the field-dissolution rates based on the steady-flow derived calibration relationship, we would have overestimated the steady flow speeds in the field.

The effects of steady flow speed and fluctuation intensity on mass transfer, i.e., gypsum-dissolution rate, were not additive. However, flow intensity (Eq. 3) includes both steady flow speed and fluctuation intensity in a single flow measure and thus represents total water motion better than either steady flow speed or fluctuation intensity. The gypsum-dissolution technique can give reasonable results as an integrative measure of flow intensity or water motion for specific ratios of steady flow speed and fluctuation intensity, but a calibration derived at one ratio is invalid at other ratios; relationships are not universal.

Our field location in Chesapeake Bay experienced short wave periods similar to the turbulence timescales we also measured (unpubl. data). However, longer wave periods may be an additional variable affecting diffusive boundary-layer thickness and gypsum dissolution that was not addressed in this study. Bilger and Atkinson (1992) suggested that strong wave surge with 10-s period swells may have contributed to mass transfer of nutrients to their coral reef flat community. Gaylord (1999) measured wave periods of 8 to 18 s in a rocky intertidal location. Gypsum-dissolution techniques are often used in the intertidal zone (e.g., Sanford et al. 1994; Leonard et al. 1998), and wave period should be considered here as an additional measure that may affect mass-transfer rates. Wave period is directly related to wave frequency (Wave period = 1/wave frequency). Whereas cage or mesh wakes represent smaller scale turbulent fluctuations, oscillatory stirring and wave action may include larger scale turbulent fluctuations, depending on oscillation or wave frequency. Increasing wave frequency leads to an increase in the wave friction factor (Jonsson 1966), which leads to an enhanced shear velocity and a decreased diffusive boundary-layer thickness (Dade 1993), and thus to an increased mass-transfer and gypsum-dissolution rate. Similarly, the frequency of any oscillatory flow may affect diffusive boundary-layer thickness (Carpenter and Williams 1993), and an increasing oscillatory frequency has been shown to increase mass transfer (Jaeger 1998; Nishimura et al. 1998). Moreover, in flow environments with longer period waves,

steady flow speed, turbulence intensity, and wave period may interact in complex ways that may not make any 'water motion' measurements possible using gypsum-dissolution techniques. Further investigation is needed.

Overall, the gypsum-dissolution technique can be used to measure steady flow speed, fluctuation intensity, or flow intensity only after a series of rigorous checks has been performed. To check if the gypsum-dissolution technique can be used as an integrative measure of 'water motion'; the following steps should be followed:

1. Choose the specific flow variable of interest.
2. Determine the flow environment, i.e., the ratio of steady flow speed to fluctuation intensity in the water body of interest. This can be done by simultaneously measuring steady flow speed (Eq. 2) and fluctuation intensity (Eq. 3) using an instrument that is capable of sampling at $\geq$1 Hz. A variety of rapid sampling current meters can be used, and they are becoming less expensive and more available. A measurement period of ca. 10 min is frequently recommended (Gross and Nowell 1983), although any time period several times longer than the maximum timescale of fluctuations is adequate. The measurements should be repeated over sufficient time to ensure that the flow environment is not changing over time. The dominant timescales of fluctuations should also be determined. This can be done by determining the peaks in the spectra or, in purely fluctuating flow, by determining the integral timescales of turbulence (Tennekes and Lumley 1972).
3. Choose an appropriate dissolution measurement duration. A measurable gypsum loss without any large changes in gypsum sphere size or change in shape is necessary.
4. If steps 1 though 3 have been completed satisfactorily, regression relations of gypsum-dissolution rate (same size and shape objects) against the flow variable of interest can be determined under laboratory-controlled conditions in the same type of flow environment. These regression relations can then be used to estimate the flow variable of interest from dissolution measurements.

The most valuable use of gypsum-dissolution techniques used as above may be to provide higher resolution measurements of the flow variable of interest than would be possible with a limited number of current meters.

Unlike its limited utility as a measure of 'water motion', the gypsum-dissolution technique is quite valid when mass-transfer rates are of most interest. In a number of studies, gypsum plates, arranged as flush as possible with the surface, have been used to measure the diffusive boundary-layer thickness or shear velocity in benthic chambers (Santschi et al. 1983; Opdyke et al. 1987; Buchholtz-Ten Brink et al. 1989; Santschi et al. 1991). In addition, the gypsum-dissolution technique has been used to measure mass transfer from crocodile skin (Davis et al. 1980) or to predict mass transfer to experimental coral reef communities (Baird and Atkinson 1997). However, mass-transfer rates are significantly different in different flow environments.

Many studies have used gypsum-dissolution techniques to address mass-transfer problems, but the biological response variables are often inappropriately attributed to flow and not to mass transfer (Table 1, column D). For example, Gerard (1982) attached gypsum buttons that had been carefully calibrated in a linear flume to *Macrocystis pyrifera* blades in a high wave and dense kelp bed environment to determine nutrient uptake by a dense stand of giant kelp, i.e., a mass-transfer problem. She estimated steady flow speeds of equal to or less than 4 cm s^{-1} from dissolution of the buttons, but noted that the steady flow speeds had appeared only on the order of 1 cm s^{-1} (Gerard 1982). Komatsu and Murakami (1994) measured flow speeds of 1.6 cm s^{-1} with a current meter in a macrophyte forest, whereas flow-speed estimates using gypsum-dissolution techniques at the same location were much higher with 5.7 cm s^{-1}, but they attributed the discrepancy to salinity effects. Gerard's (1982) and Komatsu and Murakami's (1994) wave-dominated environment with dense macroalgal biomass and blade movement may have produced a fluctuating-flow or mixed-flow environment (see Koehl and Alberte 1988 in Table 2). The dissolution rates likely were due to the effect of the fluctuations due to waves or biological roughness on diffusive boundary-layer thickness, rather than to the effect of steady flow speed on diffusive boundary-layer thickness. Gerard's (1982) final conclusion that this macroalgal stand was not nutrient limited was likely correct. However, the dissolution experiments should be interpreted in terms of enhanced mass transfer due to fluctuations in the flow and not in terms of flow speed.

Incorrect determinations of 'water motion' from gypsum-dissolution measurements taken in different flow environments may lead to incorrect conclusions in some cases. Many studies of physical–biological interactions that use dissolution techniques do not address mass-transfer problems, but address questions that depend directly on flow estimates. Such questions include particle transport to animals on reefs or near rocks and animal growth (Cusson and Bourget 1997; Bartol et al. 1999), the effect of flow on plant or animal morphology (Gerard and Mann 1979; Molloy and Bolton 1996), or the effect of flow on community composition (Cusson and Bourget 1997; Leichter and Witman 1997; Leonard et al. 1998) (Table 1, column D). Often no relation is found between flow measured using dissolution techniques and the biological variable of interest, although there might be a relationship if a more reliable measure of flow was used (e.g., Newsome and Aalto 1987; Bartol et al. 1999).

The diffusion index factor (Doty 1971), determined by dividing the weight loss of gypsum exposed to flow in the field by the weight loss of gypsum in still water of the same temperature and salinity, has often been used to compare water flow between different habitats. Still-water calibrations to determine this as a ''measure of the degree to which diffusion or dissolution was enhanced by water movement'' (Doty 1971) have given variable results (Muus 1968; Doty 1971) but have been widely used. The variability in the still-water measurements has been attributed to the small water volume used (Jokiel and Morrissey 1993; Thompson and Glenn 1994), which may have led to less of a concentration gradient in the diffusive boundary layer, and thus a low dissolution rate or saturation of Ca^{2+}. In addition, the variability has been attributed to placing gypsum devices too close to the bottom of containers (Thompson and Glenn 1994), thereby decreasing the concentration gradient in the diffusive boundary layer and decreasing dissolution rates. Gypsum loss upon retrieval can also be a significant contribution to

the total gypsum loss in still-water gypsum spheres or when the dissolution rates are low, which may increase variability.

To circumvent the volume problem, Thompson and Glenn (1994) suggested placing gypsum objects not too close to the bottom in large-volume still-water containers. Jokiel and Morrissey (1993) suggested the use of field containers with holes for still-water measurements, as the holes would allow some water exchange. However, in these containers fluctuation intensity may be high due to the perforations and small water exchange, and any dissolution rates found may in fact be due to fluctuations. Owing to the host of problems involving still-water measurements and the effect this number has on the diffusion index factor, we recommend, as did Thompson and Glenn (1994), discontinuation of the diffusion index factor concept to determine mass transfer from gypsum dissolution.

Clearly, gypsum-dissolution rate also depends on object size, as demonstrated by our calibrations of dissolution rates to steady flow speeds from 3- and 5-cm spheres. Because many sizes and shapes of dissolution objects are used in dissolution studies, a correct relationship for each has to be established or, alternatively, some standard size might be established. Theoretical calculations of mass-transfer rates of the 5-cm spheres from the mass-transfer rates of 3-cm spheres using the total wetted surface area (Eq. 5) as suggested in Pasciak and Gavis (1974) resulted in a large overestimate in gypsum-dissolution rates for given steady flow speeds. We found a close agreement between the theoretical and our experimental dissolution rates for 5-cm spheres using instead a ''characteristic dimension L'''' (Pasternak and Gauvin 1960). This characteristic dimension L'' was experimentally determined for different sizes and shapes of objects and their projections to the main flow direction in a steady-flow environment (Pasternak and Gauvin 1960). Gypsum dissolution may not be even around the spheres, and L'' only uses a fraction of the sphere wetted surface area (eq. 6, Pasternak and Gauvin 1960), unlike the equation by Pasciak and Gavis (1974). Pasternak and Gauvin (1960) suggested that L'' would ''account better in an integrated way (as distinct from local) for the average thickness of the boundary layer.'' For spheres, L'' is equivalent to sphere diameter.

One possible explanation for the smaller than expected difference in mass transfer between sphere sizes is a large change in the drag coefficient and a subsequent movement of the separation point and a change in boundary-layer turbulence and the area of the sphere affected by turbulence. However, over the range of Re numbers that our 3- and 5-cm spheres were exposed to in the steady flow speed calibrations (Re $\sim$ 1,500 to 9,600), the drag coefficient was about 0.7 and varied little. In addition, the size and shape of organisms affects vortex shedding behind organisms (Denny 1988), thus the shape and size of the gypsum object may also affect vortex shedding frequency. Experimentally determined eddy shedding frequencies of spheres at Re numbers of 200 to 3,000 showed that the backs of spheres may be affected differently at different Re numbers (Sakamoto and Haniu 1995). Another possible reason for the difference in gypsum dissolution between sphere sizes is that we used a temperature correction from Jokiel and Morrissey (1993) that was not locally verified. Scaling dissolution of different size objects in different environments clearly needs more study.

Conclusions

A rigorous series of checks and calibrations is necessary to determine if the gypsum-dissolution technique can be used to determine steady flow speed, fluctuation intensity, or flow intensity in natural flow environments or in experimental ecosystems. We recommend using the gypsum-dissolution method as a measure of steady flow speed in steady flow speed dominated environments only and as a measure of fluctuation intensity in fluctuation-dominated environments only. Appropriately calibrated, the gypsum-dissolution technique can also be used to determine flow intensity in different flow environments, a total 'water motion' measure that integrates the additive effects of both steady flow speed and fluctuation intensity. However, in our experiments the effects of steady flow speed and fluctuation intensity on gypsum dissolution were not additive such that calibrations would need to be done with the correct ratio of steady flow to fluctuation intensity. In addition to temperature and salinity corrections, dissolution rates have to be corrected for gypsum object size and shape before using them to estimate flow speed. We discourage using the gypsum-dissolution technique to compare flows between different flow environments. In addition, we recommend not using the dissolution method as an integrative measure of 'water motion' if the flow is variable over the time the gypsum objects are deployed or if the flow switches between different states. Furthermore, we recommend not using the gypsum-dissolution method to measure steady flow speed or fluctuation intensity in mixed-flow environments ($1 < u_{\text{steady}}/q < 4$). Though the gypsum-dissolution method clearly needs to be used with caution, it can be applied in exclusively steady-flow or fluctuating-flow environments with prior knowledge about the flow environment, including the dominant timescales of fluctuations. Limited to these situations, the gypsum-dissolution technique can be an effective technique to expand limited measurement capabilities. The gypsum-dissolution technique is used best as an indicator of diffusive boundary-layer thickness and mass-transfer rate, which are different in different flow environments. The gypsum-dissolution technique is not a universal integrator of 'water motion.'

References

ANGRADI, T., AND R. HOOD. 1998. An application of the plaster dissolution method for quantifying water velocity in the shallow hyporheic zone of an Appalachian stream system. Freshw. Biol. **39:** 301–315.

ARSENAULT, D. J., P. GIRARD, AND J. H. HIMMELMAN. 1997. Field evaluation of the effects of refuge use and current velocity on the growth of juvenile Iceland scallops, *Chlamys islandica* (O. F. Mueller, 1776). J. Exp. Mar. Biol. Ecol. **217:** 31–45.

BAIRD, M., AND M. ATKINSON. 1997. Measurement and prediction of mass transfer to experimental coral reef communities. Limnol. Oceanogr. **42:** 685–1693.

BARTOL, I. K., R. MANN, AND M. LUECKENBACH. 1999. Growth and mortality of oysters (*Crassostrea virginica*) on constructed

intertidal reefs: Effects of tidal height and substrate level. J. Exp. Mar. Biol. Ecol. **237:** 157–184.

BARTON, F. M., AND N. M. WILDE. 1971. Dissolution rates of polycrystalline samples of gypsum and orthorhombic forms of calcium sulphate by rotating disk method. Trans. Faraday Soc. **67:** 3590–3597.

BILGER, R., AND M. ATKINSON. 1992. Anomalous mass transfer of phosphate on coral reef flats. Limnol. Oceanogr. **37:** 261–272.

BOHLEN, W. 1977. Shear stress and sediment transport in unsteady turbulent flows. Estuar. Proc. **2:** 109–124.

BOUCKAERT, F. W., AND J. DAVIS. 1998. Microflow regimes and the distribution of macroinvertebrates around stream boulders. Freshw. Biol. **40:** 77–86.

BOWDEN, K. F. 1962. Measurements of turbulence near the sea bed in a tidal current. J. Geophys. Res. **67:** 3181–3186.

BUCHHOLTZ-TEN BRINK, M. R., G. GUST, AND D. CHAVIS. 1989. Calibration and performance of a stirred benthic chamber. Deep-Sea Res. **36:** 1083–1101.

BUSHEK, D. 1988. Settlement as a major determinant of intertidal oyster and barnacle distributions along a horizontal gradient. J. Exp. Mar. Biol. Ecol. **122:** 1–18.

CARPENTER, R., AND S. WILLIAMS. 1993. Effects of algal turf canopy height and microscale substratum topography on profiles of flow speed in a coral forereef environment. Limnol. Oceanogr. **38:** 687–694.

CRABTREE, R. W., AND S. T. TRUDGILL. 1984. The use of gypsum spheres for identifying water flow in routes in soils. Earth Surf. Process. Landf. **9:** 25–34.

CSANADY, G. 1986. Mass transfer to and from small particles in the sea. Limnol. Oceanogr. **31:** 237–248.

CUSSON, M., AND E. BOURGET. 1997. Influence of topographic heterogeneity and spatial scales on the structure of the neighbouring intertidal endobenthic macrofaunal community. Mar. Ecol. Prog. Ser. **150:** 181–193.

DADE, W. B. 1993. Near-bed turbulence and hydrodynamic control of diffusional mass transfer at the sea floor. Limnol. Oceanogr. **38:** 52–69.

DAVIS, J. E., J. R. SPOTILA, AND W. C. SCHEFLER. 1980. Evaporative water loss from the American alligator, *Alligator mississippiensis:* The relative importance of respiratory and cutaneous components and the regulatory role of the skin. Comp. Biochem. Physiol. **67:** 439–446.

DENNY, M. W. 1988. Biology and the mechanics of the wave-swept environment. Princeton Univ. Press.

DOTY, M. S. 1971. Measurement of water movement in reference to benthic algal growth. Bot. Mar. **14:** 4–7.

ECKMAN, J. E., D. O. DUGGINS, AND A. T. SEWELL. 1989. Ecology of understory kelp environments. I. Effects of kelps on flow and particle transport near the bottom. J. Exp. Mar. Biol. Ecol. **129:** 173–187.

ERFTEMEIJER, P. L. A., AND P. M. J. HERMAN. 1994. Seasonal changes in environmental variables, biomass, production and nutrient contents in two contrasting tropical intertidal seagrass beds in South Sulawesi, Indonesia. Oecologia **99:** 45–59.

FRANCE, R., AND J. HOLMQUIST. 1997. δ13 C variability of macroalgae: Effects of water motion via baffling by seagrasses and mangroves. Mar. Ecol. Prog. Ser. **149:** 305–308.

GAMBI, M., A. NOWELL, AND P. A. JUMARS. 1990. Flume observations on flow dynamics in *Zostera marina* (eelgrass) beds. Mar. Ecol. Prog. Ser. **61:** 159–169.

GAYLORD, B. 1999. Detailing agents of physical disturbance: Wave-induced velocities and accelerations on a rocky shore. J. Exp. Mar. Biol. Ecol. **239:** 85–124.

GEORGE, R. 1996. A review of Acoustic Doppler Velocimeter (ADV) tests and deployments, p. 116–120. *In* Y. C. Agrawal, A. W. Williams III, and L. Goodman [eds.], Proceedings of a Workshop on Microstructure Sensors. Sequoia Scientific.

GERARD, V. A. 1982. In situ water motion and nutrient uptake by the giant kelp *Macrocystis pyrifera.* Mar. Biol. **69:** 51–54.

———, AND K. MANN. 1979. Growth and production of *Laminaria longicruris* (Phaeophyta) populations exposed to different intensities of water movement. J. Phycol. **15:** 33–41.

GLENN, E., AND M. DOTY. 1992. Water motion affects the growth rates of *Kappaphycus alvarezii* and related seaweeds. Aquaculture **108:** 233–246.

GOERTEMILLER, T. R. 1988. Diversity of algae (Chlorophyta, Phaeophyta, Rhodophyta) related to depth, light intensity, NO_3-NO_2, and water flow across two transects of Long Reef, Grand Turk, BWI. M.S. thesis, Georgetown Univ.

GORDON, C., AND C. DOHNE. 1973. Some observations of turbulent flow in a tidal estuary. J. Geophys. Res. **78:** 1971–1978.

GROSS, T. F., AND A. NOWELL. 1983. Mean flow and turbulence scaling in a tidal boundary layer. Cont. Shelf Res. **2:** 109–126.

———, A. J. WILLIAMS, AND E. A. TERRAY. 1994. Bottom boundary layer spectral dissipation estimates in the presence of wave motions. Cont. Shelf Res. **14:** 1239–1256.

GUICHARD, F., AND E. BOURGET. 1998. Topographic heterogeneity, hydrodynamics, and benthic community structure: A scale-dependent cascade. Mar. Ecol. Prog. Ser. **171:** 59–70.

GUNDERSEN, J., B. JOERGENSEN, E. LARSEN, AND H. W. JANNASCH. 1992. Mats of giant sulphur bacteria on deep-sea sediments due to fluctuating hydrothermal flow. Nature **360:** 454–456.

HART, D. A., B. D. CLARK, AND A. JASENTULIYANA. 1996. Fine-scale field measurements of benthic flow environments inhabited by stream invertebrates. Limnol. Oceanogr. **41:** 297–308.

HOWARTH, R. W., T. BUTLER, K. LUNDE, D. SWANEY, AND C. R. CHU. 1993. Turbulence and planktonic nitrogen fixation: A mesocosm experiment. Limnol. Oceanogr. **38:** 1696–1711.

HOWERTON, R. D., AND C. E. BOYD. 1992. Measurement of water circulation in ponds with gypsum blocks. Aquac. Eng. **11:** 141–155.

JAEGER, M. J. 1998. Diffusion and dispersion in steady counterflow: A method for separation of gases using enhanced mass transport in oscillatory flow. Chem. Eng. Sci. **53:** 3613–3621.

JAEHNE, B., K. MUENNICH, R. BOESINGER, A. DUTZI, W. HUBER, AND P. LIBNER. 1987. On the parameters influencing air-water gas exchange. J. Geophys. Res. **92:** 1937–1947.

JAMES, A. N., AND A. R. R. LUPTON. 1978. Gypsum and anhydrite in foundations of hydrolic structures. Geotechnique **28:** 249–272.

JOKIEL, P. L. 1978. Effects of water motion on reef corals. J. Exp. Mar. Biol. Ecol. **35:** 87–97.

———, AND J. I. MORRISSEY. 1993. Water motion on coral reefs: Evaluation of the 'clod card' technique. Mar. Ecol. Prog. Ser. **93:** 175–181.

JONSSON, I. G. 1966. Wave boundary-layers and friction factors, p. 127–148. *In* Proceedings of the Coastal Engineering Conference 10th. American Society of Civil Engineers.

KEMPER, W. D., J. OHLSEN, AND C. J. DEMOOY. 1975. Dissolution rate of gypsum in flowing water. Soil Sci. Soc. Am. Proc. **39:** 458–464.

KOEHL, M. A. R., AND R. S. ALBERTE. 1988. Flow, flapping, and photosynthesis of *Nereocystis luetkeana:* A functional comparison of undulate and flat blade morphologies. Mar. Biol. **99:** 435–444.

KOMATSU, T., AND H. KAWAI. 1992. Measurements of time-averaged intensity of water motion with plaster balls. J. Oceanogr. **48:** 353–365.

———, AND S. I. MURAKAMI. 1994. Influence of a *Sargassum* forest on the spatial distribution of water flow. Fish. Oceanogr. **3:** 256–266.

KRAUS, N. C., A. LOHRMANN, AND R. CABRERA. 1994. New acoustic meter for measuring 3-D laboratory flows. J. Hydraul. Eng. **120:** 406–412.

LANDRY, F., T. J. MILLER, AND W. C. LEGGETT. 1995. The effects of small-scale turbulence on the ingestion rate of fathead minnow (*Pimephales promelas*) larvae. Can. J. Fish. Aquat. Sci. **52:** 1714–1719.

LAZIER, J. R. N., AND K. H. MANN. 1989. Turbulence and the diffusive layers around small organisms. Deep-Sea Res. **36:** 1721–1733.

LEICHTER, J. J., AND J. D. WITMAN. 1997. Water flow over subtidal rock walls: Relation to distributions and growth rates of sessile suspension feeders in the Gulf of Maine. Water flow and growth rates. J. Exp. Mar. Biol. Ecol. **209:** 293–307.

LEONARD, G. H., J. M. LEVINE, P. R. SCHMIDT, AND M. D. BERTNESS. 1998. Flow-driven variation in intertidal community structure in a Maine estuary. Ecology **79:** 1395–1411.

LEONARD, L., AND M. LUTHER. 1995. Flow hydrodynamics in tidal marsh canopies. Limnol. Oceanogr. **40:** 1474–1484.

LIN, W., L. P. SANFORD, B. J. ALLEVA, AND D. J. SCHWAB. 1997. Surface wind wave modeling in Chesapeake Bay, p. 1048–1062. *In* Ocean wave measurement and analysis proceedings of the conference 3rd. American Society of Civil Engineers.

LIU, S. T., AND G. H. NANCOLLAS. 1971. The kinetics of dissolution of calcium sulphate digydrate. J. Inorg. Nucl. Chem. **33:** 2311–2316.

MCGEHEE, M. A. 1994. Correspondence between assemblages of coral reef fishes and gradients of water motion, depth, and substrate size off Puerto Rico. Mar. Ecol. Prog. Ser. **105:** 243–255.

MERRELL, K. C. 1996. The effects of flow and mixing on *Vallisneria* and its associated community in experimental mesocosms. M.S. thesis, Univ. Maryland, College Park.

MOLLOY, F. J., AND J. J. BOLTON. 1996. The effects of wave exposure and depth on the morphology of inshore populations of the Namibian kelp, *Laminaria schinzii* Foslie. Bot. Mar. **39:** 525–531.

MULLINEAUX, L. S., AND C. A. BUTMAN. 1990. Recruitment of encrusting benthic invertebrates in boundary-layer flows: A deep-water experiment on Cross seamount. Limnol. Oceanogr. **35:** 409–423.

MUUS, B. 1968. A field method for measuring ''exposure'' by means of plaster balls. A preliminary account. Sarsia **34:** 61–68.

NAVAS, A. 1990. The effect of hydrodynamical factors on the dissolution rate of gypsiferous rocks in flowing water. Earth Surf. Process. Landf. **15:** 709–715.

NEWSOME, G., AND S. AALTO. 1987. An egg-mass census method for tracking fluctuations in yellow perch (*Perca flavescens*) populations. Can. J. Fish. Aquat. Sci. **44:** 1221–1232.

NISHIMURA, T., K. KUNITSUGU, AND A. M. MOREGA. 1998. Fluid mixing and mass transfer enhancement in grooved channels for pulsatile flow. J. Enhanced Heat Transf. **5:** 23–38.

NIXON, S., D. ALONSO, M. E. Q. PILSON, AND B. A. BUCKLEY. 1980. Turbulent mixing in aquatic mesocosms, p. 818–849. *In* J. P. Giesy [ed.], Microcosms in ecological research. U.S. Department of Energy.

OPDYKE, B. N., G. GUST, AND J. R. LEDWELL. 1987. Mass transfer from smooth alabaster surfaces in turbulent flow. Geophys. Res. Lett. **14:** 1131–1134.

PASCIAK, W. J., AND J. GAVIS. 1974. Transport limitation of nutrient uptake in phytoplankton. Limnol. Oceanogr. **19:** 881–888.

PASTERNAK, I., AND W. GAUVIN. 1960. Turbulent heat and mass transfer from stationary particles. Can. J. Chem. Eng. **89:** 35–42.

PETTICREW, E. L., AND J. KALFF. 1991. Calibration of a gypsum source for freshwater flow measurements. Can. J. Fish. Aquat. Sci. **48:** 1244–1249.

PORTER, E. T. 1999. Physical and biological scaling of benthic-pelagic coupling in experimental ecosystem studies. Ph.D. dissertation, University of Maryland, College Park.

SAKAMOTO, H., AND H. HANIU. 1995. The formation mechanism and shedding frequency of vortices from a sphere in uniform shear flow. J. Fluid Mech. **287:** 151–171.

SANFORD, E., D. BERMUDEZ, M. D. BERTNESS, AND S. D. GAINES. 1994. Flow, food supply and acorn barnacle population dynamics. Mar. Ecol. Prog. Ser. **104:** 49–62.

SANFORD, L. P. 1997. Turbulent mixing in experimental ecosystem studies. Mar. Ecol. Prog. Ser. **161:** 265–293.

SANTSCHI, P. H., R. F. ANDERSON, M. Q. FLEISCHER, AND W. BOWLES. 1991. Measurements of diffusive sublayer thicknesses in the ocean by alabaster dissolution, and their implication for the measurements of benthic fluxes. J. Geophys. Res. **96:** 10641–10657.

———, P. BOWER, U. P. NYFFELER, A. AZEVEDO, AND W. S. BROECKER. 1983. Estimates of the resistance to chemical transport posed by the deep-sea boundary layer. Limnol. Oceanogr. **28:** 899–912.

STEVENS, C., AND C. HURD. 1997. Boundary-layers around bladed aquatic macrophytes. Hydrobiologia **346:** 119–128.

TENNEKES, H., AND J. L. LUMLEY. 1972. A first course in turbulence. MIT.

TERRAY, E. A., AND OTHERS. 1996. Estimates of energy dissipation under breaking waves. J. Phys. Oceanogr. **26:** 792–807.

THOMPSON, T. L., AND E. P. GLENN. 1994. Plaster standards to measure water motion. Limnol. Oceanogr. **39:** 1768–1779.

WEST, J. M. 1997. Plasticity in the sclerites of a Gorgonian coral: Tests of water motion, light level, and damage cues. Biol. Bull. **192:** 279–289.

WILDISH, D., AND D. KRISTMANSON. 1997. Benthic suspension feeders and flow. Cambridge Univ. Press.

YAMAHIRA, K. 1997. Proximate factors influencing spawning site specificity of the puffer fish *Takifugu niphobles*. Mar. Ecol. Prog. Ser. **147:** 11–19.

Received: 4 January 1999
Accepted: 29 September 1999
Amended: 12 October 1999