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Physical factors: Mixing and flow

L.P. Sanford, S.E. Suttles, and E.T. Porter

Mixing and flow influence all scales of natural coastal ecosystem processes

Flow may be defined as the net movement of a fluid (or a dissolved or suspended constituent in the fluid) through a cross-section, whereas *mixing* may be thought of as exchange of a fluid or its constituents between adjacent volumes with no net directional movement. Mixing and flow are important aspects of aquatic ecosystems from the largest to the smallest of scales.

At global scales, the flows of the atmosphere and the ocean are the major engines that drive heat and nutrient fluxes through the earth's ecosystem. In the North Atlantic, the Gulf Stream carries tropical heat northward and gives Europe its temperate climate. Also, mixing of water masses across the Gulf Stream can have significant effects on the oceanic ecosystems that it separates. Movement of the warm core rings of water from the ocean side of the Gulf Stream to the continental shelf side introduces significant amounts of water low in nutrients and algae into shelf environments (Fig. 69, upper left).

At intermediate (meso) scales, mixing and flow are crucial in estuaries and coastal waters where fresh and saltwater interact. Flow and mixing of water in an estuary are intricately linked processes that determine the estuary's water exchange rate, and in so doing these processes play a major role in estuarine productivity.

At very small scales, microscopic organisms are influenced by relative motion of the fluid (shear) that is directly related to mixing intensity (Fig. 69, upper right). This shear renews nutrient and food supplies, affects contact between predators and prey, and may be a source of physical stress at high levels.

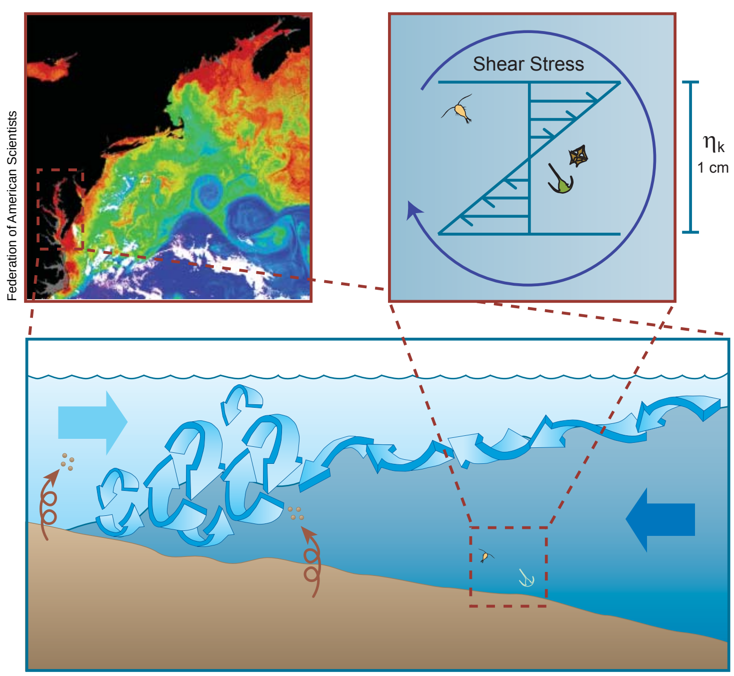


Figure 69: *Illustration of the importance of mixing and flow across all scales in coastal ecosystems (see text). The upper left panel is an enhanced satellite image of ocean color in the North Atlantic Ocean off the U.S. east coast showing low chlorophyll, warm core rings from the Gulf Stream at large scales (kilometers); the lower panel is an idealized cross-section of a partially mixed estuary illustrating mixing processes at intermediate scales (meters); and the upper right panel is a schematic diagram of the smallest turbulent eddy illustrating the mixing and flow environment at very small scales (centimeter or less).*

(η_k = Kolmogorov microscale; see next page)

Mixing is accomplished through turbulent eddies

For very slow flows at very small scales, mixing is accomplished by molecular processes. Almost all natural flows are turbulent, however, such that most mixing in nature is through the exchange of larger blobs of fluid carried by turbulent eddies. The turbulent energy spectrum (Fig. 70) helps to illustrate how turbulent energy is transferred from the large scales at which it is generated towards ever smaller scales. In doing so, this turbulent energy "cascade" mixes adjacent fluids (and their constituents) down to scales at which molecular processes can finish smoothing out gradients. The spectrum shows the distribution of velocity variance across wave number (inverse eddy size). Low wave numbers represent low frequency, large-scale processes and higher wave numbers correspond to shorter time and space scales.

Energy is highest at the low wave numbers that correspond to the largest eddies. These large eddies break down into smaller and smaller eddies, "cascading" their energy towards higher wave numbers. The range of intermediate wave numbers is called the inertial-subrange, and is characterized by a $-^{5}/_{3}$ slope on a log-log plot. The velocity spectrum starts to decrease faster than the $-^{5}/_{3}$ slope at a wave number slightly below that of the smallest turbulent eddy (Kolmogorov mircoscale, η_k). This represents a transition to a range where the energy is dissipated by molecular viscosity. Shear still exists at scales smaller than the Kolmogorov microscale, but the turbulent spatial structure disappears and gradients are uniform. The same is true for microscale distributions of nutrients, particles, salt, and temperature, except that their smallest scales (the Batchelor scales) are much smaller because their diffusivities are much smaller than the viscosity of water.

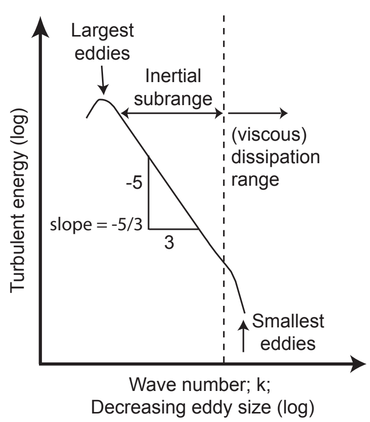


Figure 70: *Idealized velocity spectrum plot showing the cascade of turbulent kinetic energy, characterized by the -5/3 slope part of the curve on the log-log plot, from large eddies to the smallest turbulent eddies (Kolmogorov mircoscale,* η_k*). Wave number, k, corresponds to the inverse of eddy size.*

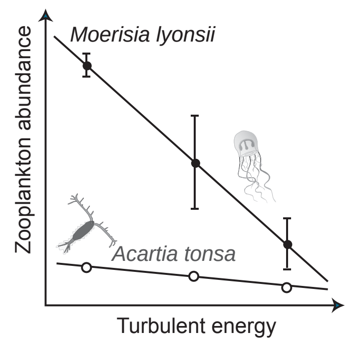


Figure 71: *Relationships between the abundance of* Moerisia lyonsii *and* Acartia tonsa, *and the turbulent energy dissipation rate (ε) in the 3 mixing treatments.*[47]

Many past mesocosm experiments suffered from a lack of mixing, but too much mixing is undesirable as well. For example, too much mixing can affect the structure of a pelagic ecosystem. As mixing energy is increased above the level to which organisms are acclimated in the environment, many organisms are damaged. In a MEERC pelagic-benthic experiment where mixing energy, as measured by the turbulent energy dissipation rate (ε) was a treatment,[46] systems that were mixed at relatively high energies had their copepod populations decline slightly and gelatinous zooplankton populations decline precipitously (Fig. 71).

47. Petersen et al. 1998

The relative importance of mixing and flow changes in pelagic and benthic environments

Mixing is biologically more important than flow in a pelagic environment and flow is more important than mixing in a benthic environment, although both must be considered in each environment (Fig. 72). Plankton in a pelagic ecosystem move with the flow of the water, so the speed of the flow itself is relatively unimportant. What matters to planktonic organisms is access to dissolved nutrients and oxygen, their encounter rates with prey or predators, and physical disturbance by turbulent mixing energy. In other words, mixing is the dominant physical influence on any given volume of the pelagic ecosystem. By contrast, many benthic organisms are attached to the bottom and are much more affected by flow. Water flow at moderate rates transports food, nutrients, and oxygen to bottom animals and plants, whereas high flow tends to exert direct physical stress on exposed organisms. Mixing is also important to the benthos because it determines the rate of exchange between the very near bottom environment and the interior of the water column. However, near-bottom mixing is directly proportional to near-bottom flow because turbulent mixing is generated by flow over the bottom.

Turbulent mixing generated by flow over the bottom is affected by the roughness of the bottom, which may be due to sediment bedforms or benthic flora or fauna that protrude into the flow. When the bottom is hydraulically smooth (in the absence of significant bed roughness), there is a diffusive boundary layer just above the sediment-water interface where molecular diffusion dominates. The thickness of this layer is an important control on fluxes of dissolved substances between sediments and the overlying water column. The thickness of the diffusive boundary layer is inversely proportional to the strength of the flow and the turbulence it generates, so higher flows result in thinner diffusive boundary layers and less diffusive resistance.

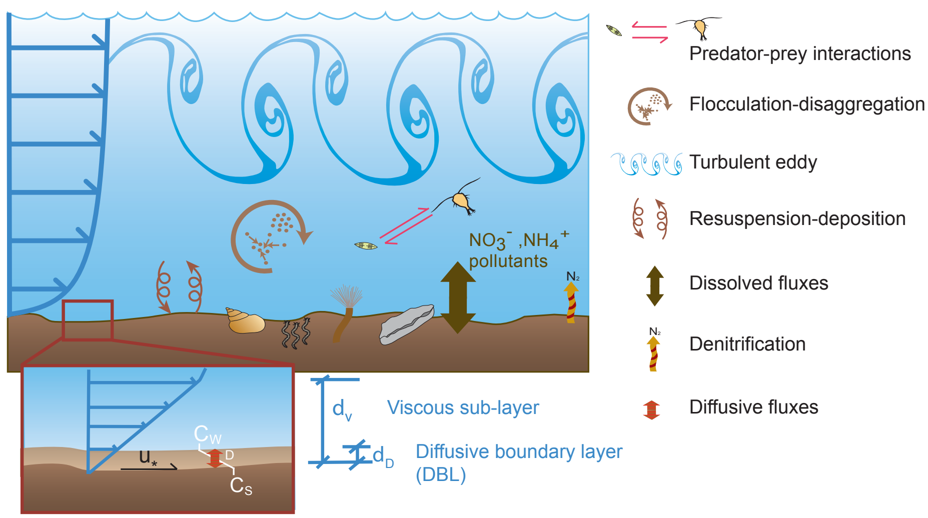
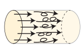
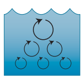
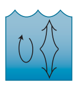
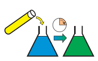
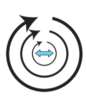
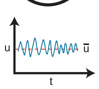
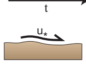
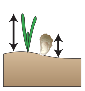
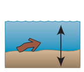


Figure 72: *Mixing and flow strongly influence many important properties and related processes in the benthic and pelagic environments of coastal ecosystems. In general, mixing is more important to planktonic organisms and water column processes, while flow is more important in the benthic environment.* C_s *is the concentration in sediment porewater and* C_w *the dissolved nutrient, oxygen or contaminant concentration in the overlying water. See Tables 8 and 9 for definition of terms and relationships.*

There are important turbulent mixing scales to be considered in mesocosm design

In the pelagic environment the most important mixing parameters are T_m, u_{RMS}, ε, l, K_Z, and η_k, whereas in the benthic environment, the important parameters are u_*, $\bar{U}$, K_b, and δ_D (Table 8). The Reynolds number Re (in one of its various configurations) reflects the state of turbulence in both environments. The number of parameters seems daunting, and it is often impossible to match all experimental ecosystem turbulence scales to those in nature. Selecting which turbulent mixing scale(s) to use will depend on the experimental system and the questions to be addressed, but mesocosm designers should understand the physical and ecological consequences of their decisions.

Table 8: *This table shows some of the turbulence scales that are important to consider when designing mixing for an experimental ecosystem.*[48]

	Parameter	Name	Description	Typical values
	*Re*	Reynolds number	Ratio of inertial to viscous forces (velocity scale x length scale / viscosity)	10^0 to 10^4 dimensionless, depends on definition
	u_{RMS}	Root Mean Squared (RMS) turbulence intensity	Characteristic turbulent (fluctuating) velocity in the water column	10^{-3} to 10^{-1} m s^{-1}
	*l*	Integral length scale	Size of the large eddies	Distance to the nearest boundary, or 10^{-2} to 10^{-1} m in the stratified interior
	K_Z	Vertical eddy diffusivity	Diffusion coefficient representing enhanced vertical mixing due to turbulence	10^{-6} m^2 s^{-1} in the stratified interior to 10^{-1} m^2 s^{-1} in an energetic bottom boundary layer
	T_m	Mixing time	Time to homogenize a tracer injected at a point	Minutes to days, depending on the size of the region of interest and the turbulent diffusivity
	ε	Turbulent energy dissipation rate	Rate of destruction of turbulent energy by viscosity and shear	10^{-7} W m^{-3} in the stratified interior of the open ocean to 10^{-1} W m^{-3} in the surface layer under breaking waves
	η_k	Kolmogorov microscale	Approximate size of the smallest turbulent eddy	10^{-3} to 10^{-1} m for the range of ε above
	$\bar{U}$	Mean flow speed	Time averaged flow speed	10^{-3} to 10^0 m s^{-1}
	u_*	Shear velocity	$= (\tau/\rho)^{1/2}$, where τ is bottom shear stress and ρ is water density; characteristic velocity scale in boundary layers	10^{-3} to 10^{-1} m s^{-1}
	K_b	Bottom roughness	Effective height of organisms or bedforms on the bottom	10^{-4} to 10^{-1} m
	δ_D	Diffusive boundary layer thickness	Thickness of layer that controls sediment-water fluxes	10^{-3} to 10^{-5} m

(Conversion of ε units: 100 mm^2 s^{-3} = 1 cm^2 s^{-3} = 1 erg g^{-1} s^{-1} = 10^{-1} W m^{-3} = 10^{-4} W kg^{-1} = 10^{-4} m^2 s^{-3}).

48. Additional guidance may be found in Sanford 1997

Well established relationships among turbulence parameters can be used to match mesocosms to nature

Fortunately there are some well-established relationships (Table 9) that can be used under many circumstances to relate the various turbulence parameters to each other. This allows characterization of the flow and mixing without measuring every quantity directly, and it limits the number of decisions to be made. For example, if the experimental ecosystem and its natural counterpart mix quickly relative to the ecological time scales of interest, the precise value of T_m is not critical. This in turn implies that the precise value of K_Z is not critical. Often, matching either ε or u_{RMS} seems to be most important for pelagic ecosystem experiments. It is usually not possible to match both because it is very difficult to match integral length scale l, which is a measure of the largest eddies; these are usually much smaller in an experimental system than in nature. Even though ε is a more commonly reported value, it often makes sense to match u_{RMS} instead because more parameters depend on its value. Similar considerations apply to the benthic environment, where u_* is considered to be of primary importance. Simultaneously matching the important parameters in both the pelagic and benthic environments in one experimental system is even more of a challenge, but it is not intractable.

Table 9: *Important turbulent mixing relationships for key parameters in experimental coastal ecosystems.*

Relationship	Comments	Where important
$u_{RMS} = \sqrt{\frac{1}{3}\left(u'^2 + v'^2 + w'^2\right)}$	Where u′, v′, w′ are the variable velocity components in the x, y and z directions	Pelagic
$\varepsilon \approx \frac{u_{RMS}{}^3}{l}$	Integral length scale, *l,* is difficult to match between nature and experimental ecosystems	Pelagic
$K_Z \approx u_{RMS} \cdot l \approx \varepsilon^{\frac{1}{3}} \cdot l^{\frac{4}{3}}$	Turbulent diffusion controls mixing in water column and is difficult to match to nature because of *l*	Pelagic
$\eta_k = 2\pi \left(\frac{\nu^3}{\varepsilon}\right)^{\frac{1}{4}}$	ν= kinematic viscosity	Pelagic
$T_m = \frac{h^2}{2 \cdot K_Z}$	Often not as critical to match exactly if well mixed *h* is total depth or width	Pelagic
$u_* = \sqrt{C_D \cdot \bar{U}}$	C_D is the hydraulic drag coefficient; depends on k_b and $\bar{U}$	Benthic
$\delta_D = \frac{10\nu}{u_*} \cdot \left(\frac{D}{\nu}\right)^{\frac{1}{3}}$	D is the molecular diffusivity (Note dependence on u_*)	Benthic

Mixing can have a variety of effects on organisms and ecosystems

The effects of large- and small-scale mixing depend on complex interactions between organism physiology and behavior, nutrient dynamics, and the light environment (Fig. 73, Table 10). On one hand, increased mixing has the potential to increase primary productivity by maintaining cells in the photic zone, by increasing phytoplankton access to benthic nutrients, by decreasing the diffusion gradient around cells, and by increasing copepod excretion rates. On the other hand, increased mixing also has the potential to decrease primary productivity by increasing the turbidity due to sediment resuspension. In addition, although large-scale vertical mixing can replenish nutrient supply to surface waters, it can also mix cells into aphotic waters, disrupting the necessary positive balance between photosynthesis and respiration. Ecosystem productivity and respiration reflect the outcome of these positive and negative effects of mixing. Few empirical studies have been conducted to quantitatively assess ecosystem level responses of plankton communities to the addition of mixing energy.

Table 10: *A summary of empirically determined effects of mixing on phytoplankton, zooplankton, and ecosystem processes from a comprehensive review of the aquatic literature.[49] (+) symbol indicates a positive relationship between the variable and turbulence, (-) indicates a negative relationship, (√) indicates the presence of a relationship, (0) indicates no relationship. (P = production; R = respiration)*

Component	Variable	Relationship
Phytoplankton	Settling rate	-
	Chlorophyll *a*	+
	Productivity	+ or 0
	Cell size	+
	Diatom / flagellate	+
	Nutrient uptake	✓
	Timing of bloom	+ or ✓
Zooplankton	Abundance	-
	Variance	-
	Predation rate	✓
	Demographics	✓
Ecosystem	Total biomass	+
	Ecosystem P, R	✓
	Nutrient dynamics	✓

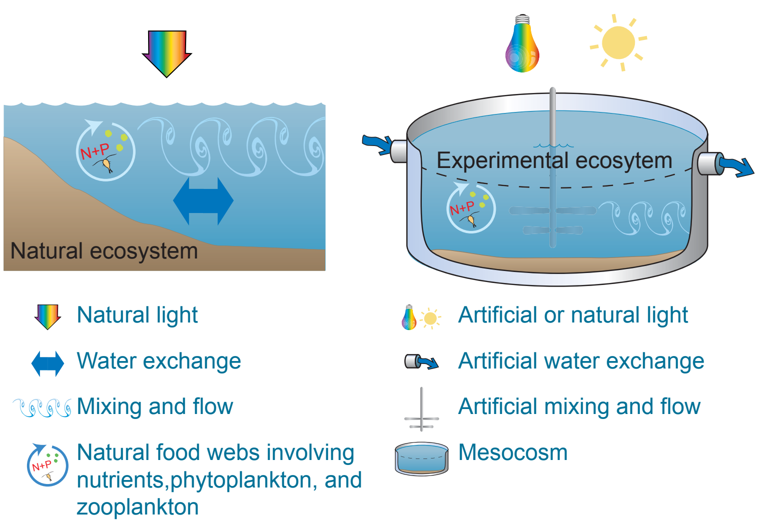


Figure 73: *Small-scale mixing around organisms and large-scale vertical mixing between surface and bottom water have a variety of effects on organisms and on ecosystem processes. Generating realistic mixing in mesocosms is challenging, but is crucial to allow for accurate ecological response to treatments applied.*

49. Petersen et al. 1998

There are many different ways to mix experimental ecosystems

The two most common techniques that are used to mix pelagic experimental ecosystems are rotating paddles and oscillating grids (or plungers). They each have advantages and disadvantages. Rotating paddles (Fig. 74), if they are carefully designed, have the advantage of promoting both stirring of the whole system and local mixing, providing uniform mixing and exposing all the contained water to turbulent energy. There is less design information about rotating paddles available in the ecological literature, however, especially for the low Reynolds number conditions most relevant for ecosystem studies. Oscillating grids (Fig. 75) are easier to quantify and to implement because their characteristics are well known, but they tend to produce large spatial gradients of turbulent energy without much overall stirring. This may be a problem for many organisms in ecosystem experiments, especially ones whose size approaches the size of the grid or whose physical structure is delicate (e.g., gelatinous zooplankton).

Another method that is sometimes used to mix pelagic experimental ecosystems is air bubbling. There are empirical relationships for turbulence and mixing induced by air bubbling, given the flow rate of air and the size of the system, that make it relatively easy to quantify mixing intensity and mixing time. The major problems with air bubbling are injection of air into the water column resulting in higher dissolved gas concentrations, spray at the surface when rising bubbles break, and potential damage to delicate organisms.

One conceptually attractive type of pelagic experimental ecosystem is the in situ enclosure, in which a small volume of a water body is enclosed in a bag and experimentally manipulated. A classic example of this was the CEPEX (Fig. 76) experiment in the late 1970s. However, this approach is fundamentally flawed unless additional mixing is provided because the dominant source of mixing energy (vertical shear) is excluded. Mixing induced by diurnal heating and cooling remains, as well as a small amount of motion transmitted through the flexible walls, but these sources are insufficient to make up for the loss of vertical shear. CEPEX investigators found that their bags were quite under-mixed and that the ecosystems behaved unrealistically as a result.

Figure 74: *Stirrer type mixer used in 1 m^3 MEERC pelagic-benthic tanks.*

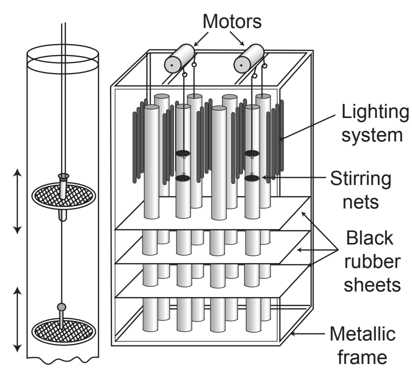


Figure 75: *Oscillating grid mixing scheme.*[50]

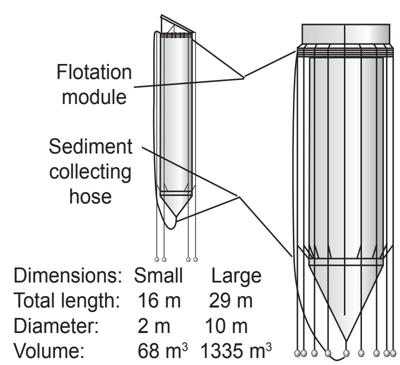


Figure 76: *Schematic of* in situ *CEPEX enclosures.*[51]

50. Estrada et al.1987, 51. Grice and Reeve 1982

Experimental benthic systems require special methods for mixing and flow

The most important mixing parameter to replicate in benthic experimental ecosystems is shear velocity, (u_*). Shear velocity can be regulated in flumes in which water flow over the bottom generates turbulence and mixing. An attractive flume design for experimental ecosystem work is an annular flume (Fig. 77), in which a revolving lid drives continuous recirculation of the water. The resulting flow characteristics are not as realistic as those produced with other flume designs. However, because water volume is contained in an annular flume as opposed to a flow-through flume system, it is well suited for experimental ecosystem studies. One disadvantage of laboratory flume systems is their cost, usually limiting replication. In additon, they are typically only practical for studies of the very near-bottom environment.

None of the pelagic mesocosm mixing systems described on the previous page produce realistic bottom shear velocity without over-mixing the water column. As part of MEERC there was an effort to develop a mixing system that generated realistic shear at the bottom while maintaining a pelagic water column with reasonable mixing energy.[52] The first attempt at such a device was a modified 1 m^3 pelagic tank with realistic water column turbulence coupled to the annular flume.

Figure 77: *Photo of annular flume that was used in benthic-pelagic coupling experiments in MEERC. Flume is 1.80 m O.D, with a 20 cm wide channel and a 15 cm water depth and a 1 m^2 sediment surface area.*

The linking of the systems proved difficult and, although the device was successful, it was costly and difficult to operate.[52]

A system that achieved both goals (i.e., realistic mixing and bottom shear) in a single tank (Fig. 78) was designed and implemented in two sets of three 1 m^3 experimental ecosystems studying the effects of sediment resuspension and benthic exchange in eco-toxicology and benthic-pelagic ecosystem studies. This system is simpler to use and is less expensive. Thus, greater replication is achievable without the complexities inherent in linked systems.

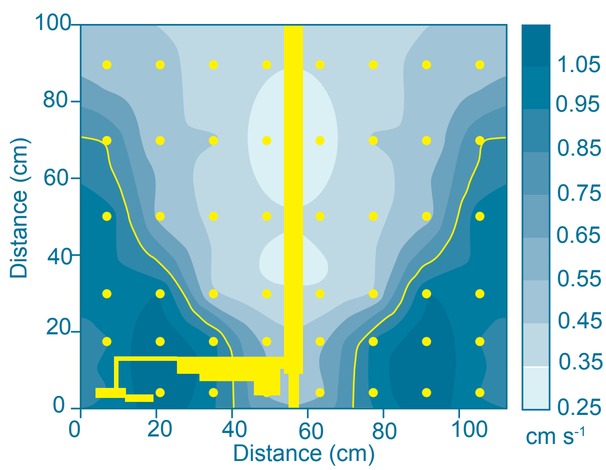


Figure 78: *Contours (left) of turbulence intensity, u_{RMS}, for new mixer design (see photo below) that achieved simultaneously uniform bottom shear stress (or friction velocity, u_*) and realistic water column u_{RMS}. Dots indicate measurement locations.*

52. Porter et al. 2004b

Principles from engineering studies are useful guides for designing mixing systems

Engineers have long been concerned with mixing and flow in tanks and channels. In designing mixing reactors for industrial processes and channels (or conduits) for flows of all types of fluids and slurries, engineers have developed many useful techniques, relationships, and rules-of-thumb that are helpful for design of mixing schemes for enclosed experimental ecosystems. The use of scale models (p.72) is one engineering technique that was employed when developing the MEERC pelagic-benthic mixing systems. Although turbulence in the models did not scale quantitatively to the full scale prototypes, the models provided valuable qualitative information on mixing and flow patterns and paddle arrangements and they allowed relatively inexpensive testing of preliminary designs. Several rules-of-thumb, such as the best ratio of mixing paddle diameter to tank diameter, optimal paddle distance above the bottom or below the surface, and paddle spacing, were used (Fig. 79). All are found in the chemical engineering literature.[53]

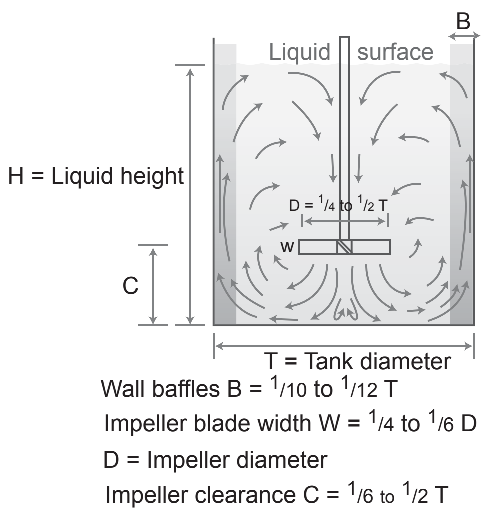


Figure 79: *Standard tank geometry for chemical engineering mixing tanks[48] with axial impeller and associated flow pattern.*

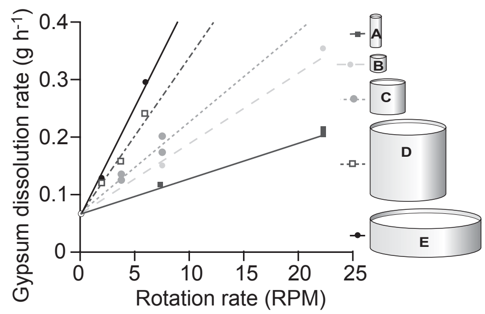


Figure 80: *Weighted average rate of gypsum dissolution (symbols) in the five different MEERC pelagic-benthic tanks compared to the cube root of the mixer power as defined by power number theory (lines). A single arbitrary constant for all tanks, which was directly related to the mixer power number, N_p, had to be calibrated to produce the theoretical curves.*

Many of the engineering studies in which these design principles were developed used much higher mixing energies than appropriate for most experimental ecosystems. However, the design principles still apply because researchers can use dimensional analysis, drawing on principles of similitude. One dimensionless number from the engineering literature that is useful is the Power Number, N_p, which behaves much like a drag coefficient. In the MEERC pelagic-benthic systems, relationships between gypsum dissolution rate (a proxy for u_{RMS} in this case) and mixer RPM in a variety of tanks scaled very well using a N_p relationship from the chemical literature (Fig. 80).

There are many other examples of engineering information that is useful for experimental ecosystem design. Collaboration with civil or chemical engineers, and referring to standard engineering literature, are useful steps when considering the design of a new experimental ecosystem facility.

53. Tatterson 1991

Mixing and flow must be quantified in experimental ecosystems

Although mixing and flow are clearly important in a qualitative sense, their potential effects on ecosystem structure and function make it essential to quantify their levels and distributions in experimental ecosystems. Intuition about how vigorously or gently to mix a scaled-down piece of nature is not always reliable.

A simple technique to measure flow patterns and mixing times in scale models and full-scale tanks is the use of tracers. In MEERC scale model studies, a food coloring dye diluted to have a density very close to that of the water in the tank was used (Fig. 81). This allowed observations of circulation patterns and tests of the adequacy of different mixer arrangements. A fluorescent dye, Rhodamine–WT (Fig. 82), was used in the full-scale tanks as this dye is detectable at very low concentrations with a properly configured fluorometer. This allowed measurements of the time it took the tank to become thoroughly mixed (T_m) when a pulse input of dye was injected at various locations in the tank. In the MEERC marsh mesocosms, bromide was used as a tracer to measure the flow rate of the groundwater through the sediments.

Tracer studies are useful for measuring flow patterns and mixing times but they are usually not adequate for measuring characteristic flow parameters. Direct flow methods (velocity probes or hot wire/film anemometry) and gypsum dissolution can be used to quantify these other parameters (e.g., Fig. 83); they are discussed in the following pages.

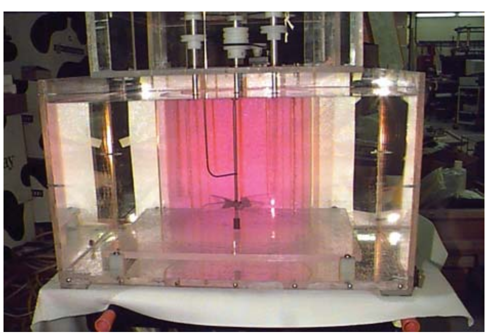


Figure 81: *Photo of scale model setup for testing of mixer designs. Diluted food coloring was typically used as tracer in scale models. All tests were video taped.*

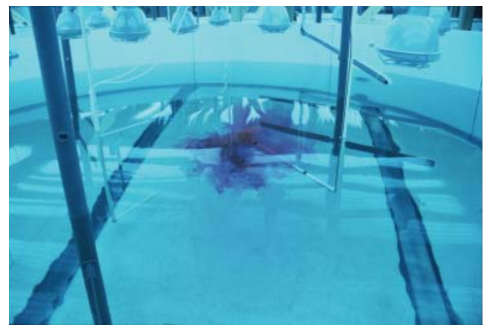


Figure 82: *Photo of Rhodamine-WT dye studies in full scale tank. Water samples were collected at timed intervals for fluorometric analysis. Mixing time, T_m, was estimated from these tests.*

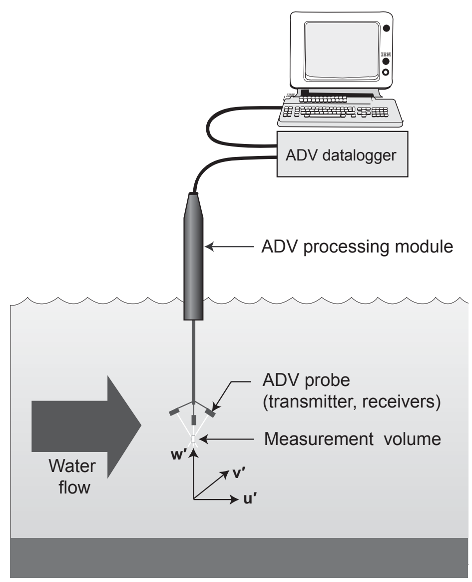


Figure 83: *Schematic diagram of acoustic doppler velocimeter (ADV) used for direct flow measurements. (w', v', u' are the variable velocity components in the x, y and z directions.)*

There are various methods for quantifying mixing and water flow

The best way to quantify turbulence and flow in experimental ecosystems is to measure these factors directly at a number of points on a very small scale with highly accurate instruments. Acoustic doppler velocimeters (Fig. 83) are relatively inexpensive, easy-to-use instruments for measuring velocity components in three dimensions (x, y, z) in a small sampling volume. From these instantaneous measurements one can calculate the mean flow and turbulent fluctuations directly. Acoustic doppler velocimeters were used in MEERC to quantify dissipation of turbulent kinetic energy, ε, and turbulence intensity, u_{RMS}, in the water column of the tanks. By taking measurements at strategic locations within the tank, these quantities were mapped out (Fig. 84), averaged over the water volume, and compared to values measured in natural systems. The average values, range of values, and spatial distributions of values were all quantified. Other direct flow measurement techniques are available as well, including laser velocimetry and hot wire/film anemometry, but they tend to be more expensive and more difficult to use.

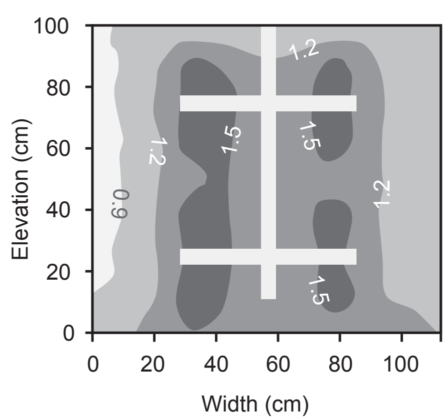


Figure 84: *Contour plot of water column turbulence intensity, u_{RMS}, cm s^{-1} calculated from acoustic doppler velocimeter and gypsum dissolution measurements in 1 m^3 pelagic-benthic tanks with standard stirrer type mixer.*

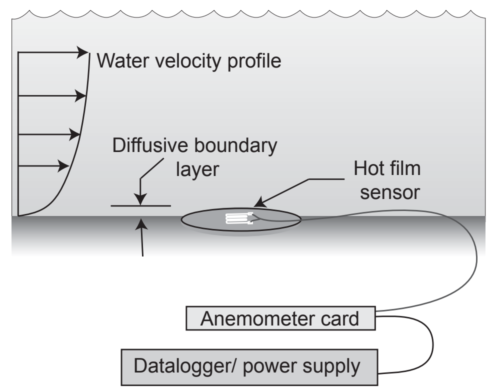


Figure 85: *Schematic diagram of hot film anemometer sensor used for direct measurements of boundary layer friction velocity, u_*.*

For the benthic environment it is important to measure the distribution of shear velocity over the bottom. Hot film anemometers are devices that can be used for this purpose (Fig. 85). The sensor measures the rate of heat loss to the water column, which is controlled by the thickness of the diffusive boundary layer, which, in turn, is inversely related to shear velocity u_*. These sensors were used extensively in the MEERC program while developing a new mixing device that would better simulate natural benthic boundary layer flows in a standard cylindrical tank (Fig. 78). In addition, these sensors can also be used on the walls of tanks, for instance to help quantify diffusive transport processes from the walls to the water column.[54]

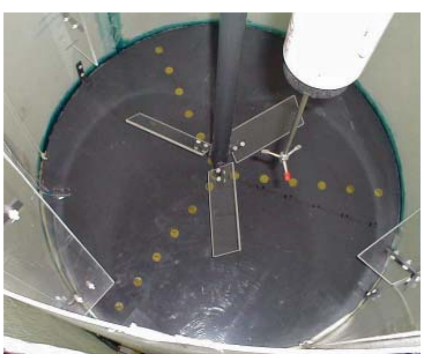
It is strongly recommended that researchers using experimental ecosystems undertake measurements that allow the direct calculation of the important flow and mixing parameters. In situations where these measurements are not feasible there are other methods available, such as gypsum dissolution. However, these indirect methods can be misleading if not properly interpreted; therefore, they should be used with caution.

54. Crawford and Sanford 2001

Gypsum dissolution can be used in some circumstances

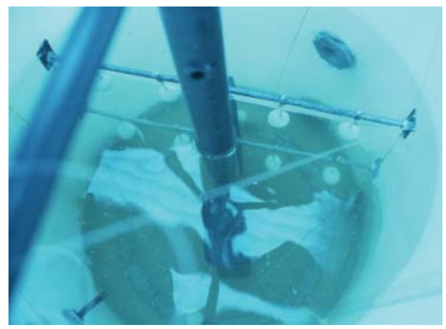
Direct flow measurement techniques (Fig. 86), although they are becoming simpler and less expensive, are still somewhat daunting for researchers without specific training in fluid dynamics. Nevertheless, much of the direct flow data in MEERC was collected by graduate students with undergraduate biology degrees. Gypsum dissolution (Fig. 87) has been suggested as a low-technology alternative to direct flow measurement for ecological studies. However, gypsum dissolution could not be used universally to measure the characteristics of flow in the MEERC tank studies. Nevertheless, if the basic characteristics of a flow are known and gypsum dissolution rates are appropriately calibrated, gypsum dissolution can be a useful tool for interpolation and extrapolation of sparse direct flow measurements.

A workable solution involves limited direct flow measurements to determine whether the velocity field is dominated by unidirectional steady flow or by fluctuations with very little mean velocity, because the response of gypsum dissolution to flow changes significantly under these different circumstances. For example, while gypsum dissolution was linearly proportional to turbulent intensity, the slopes of these relationships varied with flow regime (Fig. 88). Steady flow produces less dissolution than fluctuating flow for a given turbulence intensity. The gypsum configuration is also important, including the shape of the dissolution objects, their specific chemistry, and the chemistry and temperature of the water.[55]



Elka Porter

Figure 86: *Mixing design test tank with direct flow measuring sensors; hot-film sensors (yellow circles along tank bottom), and accoustic doppler velocimeter (3-pronged probe). This setup quantifies water column turbulence and bottom friction velocity for improved mixer design.*



Larry Sanford

Figure 87: *Gypsum ball arrangement in a MEERC pelagic-benthic tank. Gypsum balls were deployed on metal rods, covering important regions of the tank.*

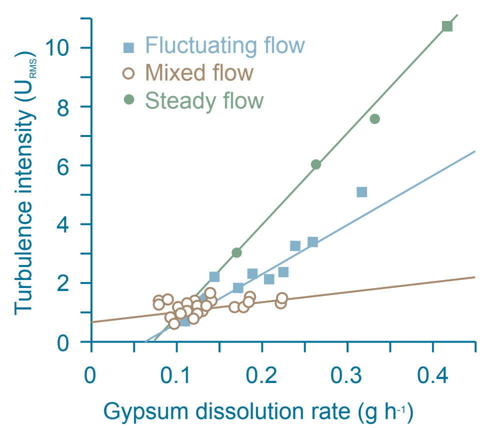


Figure 88: *Turbulence intensity versus gypsum-dissolution of 3-cm spheres in three flow environments; fluctuating environment (n = 15), mixed-flow environment (n = 33), and steady-flow environment (n = 4). Any data points with dissolution rate below 0.07 g h^{-1} were discarded. The plot reveals that inter-comparison of gypsum dissolution rates for different flow environments is not valid. Similar turbulence intensities can result in significantly different gypsum dissolution.*[55]

55. Porter et al. 2000

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