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doi: 10.2306/scienceasia1513-1874.2006.32(s1).043

Inexpensive Water Motion Measurement Devices and Techniques and Their Utility in Macroalgal Ecology: A Review

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ABSTRACT: Water motion and wave impact are, together, major determinants of the abundance and distribution of benthic intertidal marine organisms. Relatively simple techniques and devices that measure water motion and wave impact exist, and range from qualitative approaches (e.g. measurements of fetch), to integrative measures (dissimilar metals), to one-time maximum wave impact devices (drogues). We discuss the advantages and disadvantages of these devices and techniques, and provide examples of their use in marine benthic ecology. More complex devices such as arrays of electronic sensors that measure wave height and water motion continuously over very short time intervals are more expensive and are not discussed in detail.

KEYWORDS: water motion, drogues, waves, gypsum blocks, dissimilar metals, macroalgal ecology.

INTRODUCTION

Water motion is a major force driving the ecology and evolution of macroalgae. Water motion can affect macroalgae directly through physical disturbances causing tissue breakage or dislodgement of the holdfast[1-6], or by increasing the flow at the surface of the thallus, favouring nutrient and gas exchange and thus algal productivity and growth[7-9]. Water motion can also directly affect gamete transport, spore dispersal and settlement success[10-12]. Indirectly, water motion can affect survival of macroalgae and community composition by modifying the behaviour of herbivores, the importance of biotic interactions, and the magnitude of thermal and desiccation stress[13-20]. For example, Wing et al.[16] showed that water motion has a strong effect on light in multilayered macroalgal stands; mechanical disruption of the canopy cover by waves travelling through it increases light penetration to the understory and decreases self-shading within the canopy itself. Despite its importance, precise measurement of water motion *in situ* remains a challenge.

The goal of this paper is to review water motion measurement techniques and their utility in macroalgal ecology. As such, this is not an exhaustive review as we emphasize techniques that are appropriate for measurement of flow on wave-swept shores and subtidal environments. We focus on devices that can be readily constructed, are relatively inexpensive to build, and are simple to maintain and read in the field; such instruments facilitate placement of multiple devices at different locations, enabling the investigator to compare water motion at different locations simultaneously. We refer the reader to the literature for a description and discussion of the use of electronic devices to measure water motion.

The methodology for measuring water motion varies from cartographic approaches to the construction and placement of physical devices at the appropriate study sites. Cartographic methods may incorporate measurements of open-water (fetch) bordering a study site, frequency of winds blowing from specific directions, and sometimes, local bottom topography, to obtain an Exposure Index. Physical devices include those in which weight lost to dissolution is used to estimate water movement, and others that measure the actual force of wave impact on a shore. Some devices measure water flow, others measure the force generated by water flow and wave impact; which technique or device is used depends on the requirements of the investigator. Each technique is described separately, along with suggestions for use. We also include a summary table that lists the various techniques/devices discussed, their approximate cost, and advantages and disadvantages.

FETCH BASED INDICES

Fetch-related exposure indices are based on wind speed and fetch (the maximum distance wind can blow unimpeded across a stretch of water) to predict the size (height) of wind-generated waves.

The index described here has been developed by the Physical Shore-Zone Mapping Task Force of British

Columbia, Canada[21], and is based on standard engineering practices for estimating wave heights for a particular shore unit or site[22]. Engineering practices involve the use of complex wave climate models that combine fetch characteristics with historical wind-climate measurements and wind-wave generation, wave refraction and shoaling information. The goal of the Mapping Task Force was to develop a method for estimating wave exposure that could be easily calculated, making it accessible to non-engineers, and still retaining reasonable accuracy. The technique is intended to be part of a common set of inventory mapping standards for the coast of British Columbia. Since this particular method ignores local wind climate and wave refraction, it should be considered as a first approximation of wave exposure.

The method takes into account two indices of fetch: modified effective fetch and maximum fetch. Modified effective fetch involves the measurement for a particular site of fetch distances along three vectors, the shore-normal (perpendicular to the general trend of shore line) and 45° to left and right of the shore-normal. Modified effective fetch is calculated using the following equation:

$$Fe = \frac{\sum(\cos\theta_i) \times F_i}{\sum \cos\theta_i}$$

where Fe is the effective fetch in km, θ_i is the angle between the shore normal and the direction (0°, 45° to the left and 45° to the right), and Fi is the fetch distance in km along the relevant vector22. Modified effective fetch estimates the contribution of locally wind-generated waves while maximum fetch accounts for the contribution of waves generated in areas remote from the site such as the open ocean, but which can propagate onto the shore. Maximum fetch provides an index of swell waves and is defined as the maximum fetch distance in km measured from the site. By convention, a value of 1000 km is used when open-ocean fetches occur, that is fetch lines directed into the open-ocean[21].

Measurements of modified effective fetch and maximum fetch are then used to determine the wave exposure class of a particular site (Table 1). Exposure classes are derived from prior knowledge and cross-tabulation of maximum fetch and modified fetch measurements (Table 1). This method has been compared to an intertidal biotic assemblage-based index of wave exposure and is reported to agree reasonably well, showing 75% agreement between the two methods[21].

A fetch-based index offers at most a rough measure of wave exposure, it has the advantage of being objective and repeatable, i.e. different workers will obtain the same index. It is a rough measure because it averages wave exposure over distance and time, and thus has limited spatial and temporal resolution. As well, this procedure as described here does not factor in nearshore topography, an important factor in how waves build onto the shore (however see [22-24]). This metric is simple to compute, though potentially time-consuming, and requires no presence on the shore.

Biologically Defined Exposure Indices

Ballantine[25] and Lewis[26] were among the first to propose a biologically defined exposure index (= BDEI) based on the abundance of marine organisms and their observed distribution in response to wave impact. This approach is not universally applicable as the composition and sensitivity of communities differs from one site to another, precluding direct comparisons over larger spatial scales[25-26]. BDEI also assumes that no factors other than wave action influence the biological communities examined[25-27]. Bell and Denny[27] showed that a site classified, *a priori,* as moderately exposed using qualitative observations of water motion and community assemblages, experienced much greater hydrodynamic disturbance (as measured with drogues) than was first assumed, suggesting caution in the use of qualitative descriptions and biological indices to explain and predict specific ecological patterns and processes.

Once a BDEI is constructed, it does have the benefit of integrating the organisms of interest (to the ecologist) into the index, even if these organisms have a limited range. A disadvantage of the BDEI is that it incorporates no direct measure of wave exposure; hence it cannot be directly compared to any of the other measures discussed here.

Others have used morphological measurements of macroalgae as an indicator of water motion. But using morphological patterns to determine exposure to water motion is a circular argument, as are indices based on

Table 1. Wave exposure classes based on modified-effective fetch and maximum fetch (after[21]).

	Modified-effective fetch (km)				
Max fetch (km)	<1	1-10	10-50	50-500	>500
<10	VP	P	n/a	n/a	n/a
10-50	n/a	SP	SP	n/a	n/a
50-500	n/a	SE	SE	SE	n/a
>500	n/a	n/a	SE	E	E

VP: Very protected, usually the location of all weather anchorages, marinas and harbours.
P: protected, usually areas of provisional anchorages and low wave exposure except in extreme winds.
SP: semi-protected, waves are low most of the time except during high winds.
SE: semi-exposed, swells generated in areas distant from the shore unit create relatively high wave conditions; during storms, extremely large waves create high-wave exposures.
E: exposed, high wave conditions usually prevail within this exposure category, which is typical of open-ocean conditions.

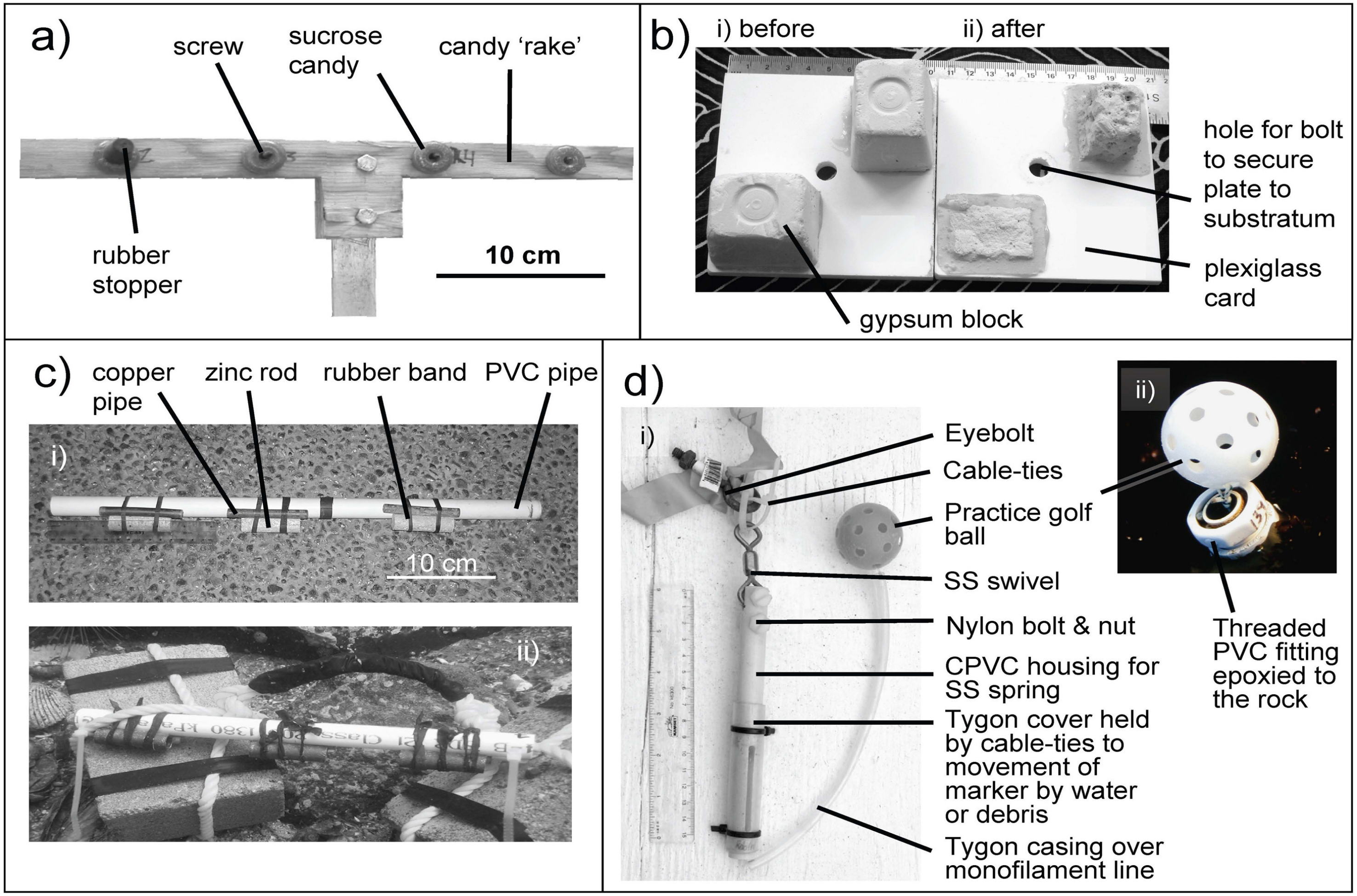

Fig 1. a) Picture of a candy 'rake' used to measure the rate of dissolution of sucrose candy (Lifesavers^{TM}.) as an estimate of relative water motion. b) Picture of gypsum blocks used to measure the rate of dissolution of gypsum as an estimate of relative water motion; i) before and ii) after immersion (note: lower block in ii) was lost). c i) Picture of a dissimilar-metal unit used to measure the rate of dissolution of zinc as an estimate of relative water motion (picture courtesy of S. Sandwith). The sampling unit consists of a PVC pipe with three pairs of a zinc rod and a copper pipe held together with rubber bands; ii) Picture of unit in situ, (picture courtesy of A. Griffiths). d) Picture of a dynamometer used to measure maximum wave velocities on wave-swept shores. i) Sampling unit out of the water showing swivel at top end attached by cable-ties to an eyebolt; ii) Picture of a dynamometer inserted into a hole drilled into the rock exposing only the drag element.

biological assemblages: a shore is considered wave-exposed because kelps, for example, *Nereocystis luetkeana*, have smooth, strap-like (narrow but thick) blades, and *Nereocystis'* blades are smooth and strap-like because they are subjected to high wave exposure.

Methods Based on Dissolution

Another approach to measuring water movement is to measure weight loss of a given material, such as sucrose candies (Lifesavers™, gypsum, or zinc, as a function of water movement. These methods have been widely used as a measure of 'water motion' and have proven useful for studies involving question of mass/heat transfer or nutrient/particle delivery to and from organisms[28-30], but provide little information regarding instantaneous flow magnitudes or imposed hydrodynamic forces.

Sucrose Candies

Shaughnessy[31] and Martel[32] measured weight loss of sucrose candies (Lifesavers™ that were submerged at each site for a period of 2 min. to assess differences in wave exposure among sites. Koehl and Alberte[29] used sucrose candies attached directly to the blade of the kelp *Nereocystis luetkeana* to compare water velocities along blades of different morphologies. In each case, weights of the candies are determined prior to immersion, and once again after immersion and drying. One technique for immersion is to attach pre-weighed candies to the prongs of a rake-like device, with the candies held in place by rubber stoppers (Fig. 1a). The rake is immersed for a short, measured time period (approx. 2 min.), and the candies serve as replicate measures of water motion at the site.

This method is rapid, cheap, and repeatable over a short time frame. If different sites are to be compared, it is useful to make the measurements simultaneously at each site, to minimize differences due to tidal elevations and weather.

Gypsum Blocks

This technique is similar in logic and approach to the sucrose candies technique but utilizes ice-cube sized gypsum ($CaSO_4$, plaster of Paris) casts glued, for example, to Plexiglas cards that can be variously attached to rocks in the intertidal or subtidal (Fig. 1b), or to poles anchored in the subtidal. Some authors have also successfully used gypsum buttons or nodules glued or directly moulded to a paper clip that can be clamped directly to the thallus of a kelp[7]. As with the sucrose candies, clod-cards are pre-weighed, immersed in water for 24 - 72 hrs, dried, and reweighed. The loss in weight provides a relative measure of water motion at a site, and multiple measurements can be compared among sites.

Measurements of weight loss can be converted to water velocities by using a standardized calibration curve. Such a curve can be obtained by immersing some blocks in standing water and others in waters of known velocities, all for a known length of time. However, at best, such calibration curves offer an approximation, as rates of gypsum dissolution have been found to vary with the shape of the cast, the temperature and salinity of the surrounding seawater, the abrasive action of sediment or adjacent macroalgae, and erosion due to grazers[33-35]. Furthermore, Porter *et al.*[36] suggest that gypsum dissolution rates are greatly influenced by changes in the flow environments from steady to fluctuating flow speeds and argue that the gypsum dissolution technique should not be used as an "universal integrator of 'water motion'". If these limitations are considered, however, this technique can be used and has been used extensively as a index of relative water exposure (see [36] and references therein).

Corrosion Rates of Dissimilar Metals

This technique is based on the fact that two metals from the opposite ends of the Noble scale when put into contact in seawater will corrode through electrolysis and galvanic corrosion[37]. Copper and zinc are most commonly combined due to their inexpensiveness and wide availability. A measure of absolute water velocity can be estimated by converting measurements of weight loss of the zinc (the copper remaining relatively unaffected) to standard curves derived in controlled laboratory settings, e.g. immersed in water of known velocities. Each sampling unit consist of three to six pairs of copper piping and zinc rod held together by a rubber band (usually a piece of a bicycle inner tube) and attached (also by a rubber band) to a piece of PVC pipe (Fig. 1c). The PVC pipe in turn is attached to a cement block that serves as an anchor to hold the array in place (Fig. 1c). Clearly in more wave impacted sites a more solid means of anchoring, such as bolts and cement anchors, is required.

Drogues

Disturbance and mortality due to the impact of hydrodynamic forces associated with moving water are inadequately measured by dissolution-based methods. The probability of an organism being dislodged or damaged due to the impact of a passing wave can be best estimated by determining the maximum water velocity and thus the force to which it is exposed. Drogues are instruments that measure water motion, *in situ,* by recording the maximum drag force imposed on a plate or spherical device attached to a spring. The hydrodynamic drag on the plate or sphere can be

Table 2. Summary table comparing some of the advantages and disadvantages of the various methods and instruments used for measuring flow. Refer to text for details

Method	Principle of method	Variable measured	Intertidal vs subtidal	Estimate obtained	Spatial & temporal scale	Equipment needed	Set up time	Approximate cost (CND $)	Period of deployment	Repeated use	Limitations
Qualitative	Qualitative categorization based on personal observation and knowledge	None	Applied to both	Exposed to sheltered subjective categorization	Crude; local to regional scale	None	None	None	One time categorization	n/a	Subjective
Biological	Categorization based on knowledge of marine organisms' ecology with regards to wave exposure	Presence/ absence of species	Usually intertidal	Exposed to sheltered categorization based on species assemblages present	Crude; local scale	Paper and pencil	None	Minimal	One time categorization	n/a	Based on knowledge of local marine communities' composition and their sensitivity to exposure; not applicable universally
Fetch-related cartographic method	Size of wind-generated waves depends on the fetch window (area of ocean surface over which wind can blow unimpeded)	fetch distances, modified-fetch and maximum fetch (km)	Applied to both	Index of relative wave exposure (obtained using modified-fetch and maximum fetch matrix)	Limited: average over km and months; local to regional scale	Chart, Compass, Ruler	< 5 min per site	$15-$20	One time measurements	n/a	Based on cartographical data only; does not take into account effect of bottom topography on wave size or swell contribution
Sucrose Candies	Rate of dissolution (or mass loss) of an element increases with increases in water motion	Mass loss (g)	Usually intertidal, but has also been used subtidally at micro scale	Overall/cumulative or average water motion/ mass flux; Index of relative wave exposure	Measurements taken over a few min; micro scale (flow around a kelp blade) to local scale	Candies (Lifesaver), 'broom', scale	15-30 min.	$5-$15/unit	2 min.	No (requires new candies)	Measurements affected by flow velocities but also flow turbulences
Gypsum blocks ($CaSO_4$)	As with sucrose candies	As with sucrose candies	Both intertidally and subtidally	As with sucrose candies	Average taken over 24-72 hrs; micro scale (plaster buttons) to local scale	Plaster of Paris, ice cube trays, 5 min marine epoxy, Plexiglass cards (10cmx10 cm) bolts & nuts, scale	24-72 hrs	$20-$50 for 24-48 blocks	24-72 hrs	No (requires new $CaSO_4$ blocks)	Measurements affected by flow velocities but also flow turbulences, water temperature, salinity and abrasion by neighbouring organisms or herbivores
Dissimilar metals	Rate of electrolysis (mass loss) of zinc increases with increases in water motion	Mass loss of zinc (g)	Both intertidally and subtidally	Overall/cumulative or average water motion/ mass flux; Index of relative wave exposure or absolute wave exposure if calibrated against known water flow	Average taken over 7d; local to regional scale	Zinc and copper rods, PVC piping, rubber bands, scale	1-48 hrs	$5-$10 /3 pairs	5-21d	Yes, but limited by rate of electrolysis	Zinc rods made from different batches of alloys will produce variable reactions and thus unreliable results; more durable than plaster, can be let in the field for longer thus give a better average speed of variable flow, but provides no information of instataneous flow
Drogues	An object exposed to a passing wave will experience drag force proportional to wave velocity	Spring extension (cm)	Intertidally	Maximum wave force; maximum wave velocities; Index of absolute wave exposure	Maximum over period of deployment, local to regional	Spring, CPVC piping, practice golf ball, fishing line, various fittings	24-72 hrs	$15-$25/unit	Minimum of one tidal cycle (12-24 hrs)	Yes	Provides a good approximation of the effective maximum velocities flexible macroalgae experience, however may understestimate water velocities experienced by organisms that are stiffer than the drogue because of time lag due to realignement of instrument

estimated directly by measuring the extension of the spring as the object is exposed to drag. The dynamometer (= drogue; Fig. 1d), now in common use, was designed by Bell and Denny[27], and is a modification of one developed by Jones & Demetropoulos[38].

Bell and Denny's[27] dynamometer consists of a practice golf ball (a perforated hollow plastic sphere) attached by a piece of monofilament line to a stainless steal spring housed in a Chlorinated Poly-Vinyl Chloride (CPVC) cylindrical case. As drag is exerted on the sphere, the maximum spring extension is recorded by a rubber indicator fitted snugly onto the monofilament line. The dynamometer can be either anchored to the rock by means of a stainless steel swivel in turn attached with cable ties to an eyebolt drilled into the substratum, or by inserting the CPVC housing into a hole drilled into the rock (Fig. 1d). The latter requires access to a rock drill but such placement prevents the loss of instruments due to both entanglement with algae and excessive wave surge at high wave exposure sites.

Mathematical modelling and field measurements showed that drogues provide accurate estimates of maximum water velocities on wave-swept shores when peak velocities and the period of oscillations are high. Under low peak velocities (< 5 m/s) and short-period oscillations (< 4 s), however, the deceleration of the practice golf ball and the reorientation of the housing will lead to an overestimation of the hydrodynamic force (Bell and Denny[27]).

As drogues have come into more common use, we have listed some currently useful websites about their construction and use:

1. Dr. Mark Denny's Lab web site with a detailed step-by-step description of how to built wave dynamometers: http://www.stanford.edu/group/denny/
2. One source of the springs is: http://www.asraymond.com
3. A supplier of other parts used in the drogues is: http://www.smallparts.com

Electronic Devices

A number of electronic devices capable of continuously measuring instantaneous water velocity have also been developed for use in the intertidal[34, 39] and the subtidal[40]. Such instruments provide detailed information on water velocities and accelerations in 2 or 3 dimensions at high temporal resolutions. Detailed knowledge of *in situ* flow velocities and fluctuations is essential for studies examining propagule/larval dispersal and their settlement patterns. However, these instruments can be expensive to build and/or buy (e.g. electromagnetic current meters, acoustic doppler velocimeter), usually making simultaneous measurements at a large number of locations not feasible.

Conclusion

Water motion manifests itself in a multitude of ways important to marine benthic organisms. The forces generated by waves striking the shore can tear and detach organisms, and the moving water can generate drag forces, as well as influence nutrients and physical characteristics of a body of water such as temperature, salinity, and content of gasses. Marine ecologists are frequently required to measure water motion in a way that is repeatable, inexpensive, and relevant to the research questions being investigated. We have provided an overview of such devices. Table 2 summarizes the advantages and disadvantages of each technique and device discussed, what variable each measures that is relevant to marine benthic algal ecology, and a rough estimate of cost and necessary materials.

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