Global Seagrass Research Methods
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Chapter 17

Measurements of physical parameters in seagrass habitats

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Chapter Objective

To present methods for quantifying temperature, salinity, currents, waves and turbulence in seagrass habitats and to describe simple, yet biologically relevant techniques that can be easily applied throughout the world. In many cases, an inexpensive (but limited) and a more costly (but more accurate) option are described.

Overview

Seagrass environments are characterized by physical conditions like temperature, salinity, currents, waves, turbulence and light. Each of these parameters has the potential to affect the vegetation from the smallest (molecular and physiological) to the largest (ecosystem as well as global) scale. For example, temperature and salinity affect the growth and distribution of seagrasses (Bulthuis 1987, Koch and Dawes 1991, Masini and Manning 1997) while sheltered conditions (reduced wave action and current velocity) are also often necessary for seagrasses to become established (Lee Long et al. 1993, Dan et al. 1998, van Katwijk and Hermus 2000). Conversely, seagrass beds affect these physical parameters. They reduce current velocity (Fonseca et al. 1982, Fonseca and Fisher 1986, Gambi et al. 1990, Koch and Gust 1999), attenuate wave energy (Fonseca and Cahalan 1992, Koch 1996, Verduin and Backhaus 2000), change the level of turbulence in the water (Gambi et al. 1990, Ackerman and Okubo 1993, Worcester 1995, Koch and Gust 1999), and enhance light availability by promoting the deposition of suspended sediments (Kemp et al. 1984, Short and Short 1984). As a result, there is a complex but clear feedback between seagrasses and the physical habitat they colonize. Studying the interaction between seagrasses and their physical environment may allow us to better understand the processes that influence the biology of seagrasses.

The chapter begins with the description of two simple methods of obtaining accurate temperature data in seagrass habitats, including sediments and the water column, followed by a description of how to obtain salinity data from research vessels or directly in the seagrass

habitat. It is noted that temperature and salinity can be influenced by tides and, therefore, caution needs to be taken when collecting and interpreting these data.

A large variety of current meters are presently available on the market. Their appropriateness for seagrass research is discussed and the dye tracking method is described in detail for quantification of current velocity in seagrass-colonized areas. The same technique is later applied towards the quantification of turbulence in seagrass beds. Dye tracking is a simple and inexpensive technique that will allow scientists around the world to make currents and turbulence an integral part of the analysis of their data.

Quantification of waves in seagrass habitats is described via the deployment of pressure transducers. Although simpler techniques are available to quantify maximum wave exposure (dynamometers) and wave characteristics (videotaping), pressure transducers still provide the most accurate data in seagrass habitats over the broadest range of climatic conditions.

Light is an important parameters regulating seagrass growth and distribution (Dennison et al. 1993, Bach et al. 1998, Hall et al. 1999) and is addressed in Chapter 19.

17.3 Temperature

17.3.1 Introduction

Temperature affects seagrasses from the global to the molecular level. It influences the biogeographical distribution of seagrasses worldwide (den Hartog 1970, Walker and Prince 1987, Short and Neckles 1999) as well as the enzymatic activity in individual cells (Masini and Manning 1997). As temperature tends to increase due to global changes (Houghton et al. 1996), it can be expected that its impact on seagrasses will be felt from the smallest to the largest scales (Short and Neckles 1999).

The temperature of the water within and above seagrass beds may vary locally depending on the density of the vegetation (see Komatsu et al. 1982 for density-dependent temperature in kelp beds) and the hydrodynamic conditions prevailing in the area (Koch and Gust 1999). Additionally, the temperature of the sediment can also differ from that of the water column, especially during times of the year when rapid fluctuations in temperature occur (i.e., spring and autumn). Therefore, when measuring temperature in seagrass-related studies, it is important to collect data from the appropriate location (sediment or water within, above or adjacent to the seagrass bed) and to be consistent over time. The sediment temperature may be fundamental when determining remineralization in seagrass-colonized sediments and/or root respiration. In contrast, the temperature within the vegetation may be relevant when evaluating epiphytic and seagrass growth, photosynthetic rates and fluorescence.

The simplest and most inexpensive instrument used to measure temperature in a seagrass habitat is the hand-held thermometer. Due to its temporal and spatial limitations (only collects one data point in time and space), collection of temperature data using data-loggers is also described.

17.3.2 Objective

Quantification of temperature in seagrass habitats using a hand-held thermometer or temperature logger when available.

17.3.3 Necessary Materials and Equipment

- Thermometer of your choice (electrical or fluid; mercury thermometers should be avoided due to their potential environmental hazard) as long as the following criteria are met: accuracy of 1°C for natural conditions and 0.1°C for physiological and lab studies (Fonseca 1990) OR temperature data logger with field anchoring system
- Tide table
- Data book
- Bucket or Niskin bottle (if thermometer can not be easily placed at the recording site – as when working from a ship)

17.3.4 Methods

In situ water temperature is usually determined using contact thermometers, either fluid (alcohol) or electrical. Small affordable thermometers with data loggers have also recently become available. The choice between using hand-held thermometers versus temperature loggers is determined by the frequency, duration and resolution of the data needed as well as the budget of the project. While hand-held thermometers require an individual to take the readings, the temperature loggers can collect data as often as twice per second for several days or even months. Therefore, the use of temperature loggers is encouraged when possible (see e.g., Onset Computers at http://www.envsens.com/products/onset/index.html)

Once the thermometer has been chosen, it is important to select the appropriate area where the temperature measurement will be taken. Temperatures can differ significantly between vegetated and unvegetated areas or above and within the vegetation. To maintain consistency for monitoring purposes, temperature measurements should always be taken at the same location. It is suggested that measurements be made in the middle of the seagrass canopy; these are the temperatures that have the greatest influence on the seagrasses although the site of temperature measurements may be adjusted according to the research question.

17.3.5 Data Collection

Hand Held Thermometer

1. Lower the thermometer to the selected area and allow the temperature to equilibrate (depends on the response time of each thermometer). If the sampling site is not easily accessible, water can be collected using a bucket or a Niskin bottle and the temperature should be recorded as soon as the water is brought aboard (Fonseca 1990). If the temperature within the canopy is to be measured, disturbance of the canopy and the possible temperature stratification above and within the vegetation should be avoided (the bucket/Niskin bottle method would not be appropriate in this case).
2. If possible (when scuba diving or snorkeling), read the temperature without moving the thermometer from the measuring site. If that is not possible, read the temperature as soon as possible after moving it.
3. Record the temperature as well as the location (above or within the canopy), time of the day, the tidal stage (flood or ebb) and the water depth.

Temperature Data Logger

1. In the lab, program the data logger according to the manufacturer's instructions and the research question to be pursued.
2. Select the site where the data logger is to be installed. Place a narrow pole (to avoid disturbance of the canopy and water flow) firmly in the ground and attach the data logger. Note the position of the logger in relation to the sediment and the canopy surface. If needed, mark the location with a buoy not directly connected to the temperature logger.
3. If the logger remains deployed for long periods of time (more than 2 weeks in tropical and eutrophic environments and more than a month in temperate and oligotrophic environments), it should be cleaned on a regular basis by brushing colonizing organisms off the sensor.
4. Retrieve the logger and offload the data according to the manufacturer's guidelines. This can be done in situ using a laptop computer allowing the sensor to be immediately deployed again.

17.3.6 Trouble Shooting and Hints

All thermometers and temperature loggers should be calibrated against a reference instrument (laboratory alcohol thermometer) or certified thermometer prior to use as well as on a regular basis. It should also be noted if the thermometer is a full or partial immersion thermometer. The former should always be immersed to the full column of the spirits (alcohol) while the latter only needs to be inserted such that a constant length of the thermometer is in contact with the liquid.

If temperature measurements are only taken once a day (thermometer), the readings may vary with tides. Therefore, before starting a daily or seasonal temperature measuring routine, a time series of temperature measurements covering several tidal cycles should be recorded on an hourly basis. As the tides in most parts of the world occur later every day, the effect of tides on the temperature at a given time of the day can be followed quite easily. If the water temperature is relatively constant at a given time of day, the effect of the tides may be insignificant and temperature data can be recorded independent of the tidal phase. In this case, the temperature should always be measured at the same time of the day. If the temperature changes as tidal depth changes, temperature data needs to be collected at shorter time intervals to include several phases of the tides or at a fixed tidal phase. Alternatively, the variation in temperature throughout tidal cycles as well as day/night cycles may be captured using a maximum/minimum ("max/min") thermometer.

17.3.7 Discussion

All temperatures should be expressed as degrees Celsius (°C). If possible, the use of temperature loggers is recommended as the data set will be more complete (data will be recorded independent of the weather or time of the day) and more accurate (sensor needs less time to equilibrate) than when using a hand held thermometer. Additionally, if several temperature loggers are available, this parameter can be recorded simultaneously at different locations. A disadvantage of temperature loggers is that, during long-term deployments, they need to be cleaned on a regular basis as the organisms that colonize their surfaces may

increase the response time of the logger. Alternatively, max/min thermometers can be used to identify the range of temperatures at a selected site.

Seagrass shoot density may be important to consider when interpreting temperature data collected in the sediments or within the canopy, especially in tidally dominated areas where the residence time of a water mass within a seagrass bed is affected by the density of the vegetation (Koch and Gust 1999). Temperature in vegetated areas may be a function of the density of the plants (Komatsu et al. 1982).

Salinity

17.4.1 Introduction

The salinity of the water may not only affect the distribution (Orth and Moore 1984, Fletcher and Fletcher 1995) and growth (Adams and Bate 1998, Kamermans et al. 1999) of seagrasses but can also be an environmental stress (Zieman et al. 1999) rendering seagrasses more or less vulnerable to diseases (Burdick et al. 1993). *Variation* in salinity seems to be a better predictor of seagrass biomass and diversity than *average* salinity (Montague and Ley 1993). Additionally, salinity data can be a good indicator of the origin of the water mass in the seagrass bed (oceanic or riverine) and may also provide some information about seagrass diversity and ecology in a specific area.

Salinity measurements are easier to do than they were in the days of seawater titration. Presently, salinity can be determined using refractometers, hydrometers, and salinometers based on light refraction, specific gravity (mass) and conductivity, respectively. Although the units of salinity obtained from different instruments can be expressed as practical salinity units (psu) or parts per thousand (‰), for most purposes, including seagrass research, it can be assumed that ‰ and psu are synonymous (Mellor 1996).

The use of hydrometers is not recommended especially under field conditions as their readings are affected by the concentration of suspended solids in the water. Refractometers are acceptable when an accuracy of 1 ‰ is appropriate. When a higher accuracy is needed (0.1 psu for physiological studies or to identify water masses), salinometers are recommended.

17.4.2 Objective

To determine salinity in seagrass habitats using a refractometer.

17.4.3 Necessary Materials and Equipment

- Refractometer
- Soft absorbent tissue
- Distilled water
- Tide table
- Data book
- Bucket or a Niskin bottle (if a water sample can not be easily collected from the study site – as when working off a ship)

17.4.4 Methods

Make sure the surface of the refractometer is clean by making sure the glass surface contains no particles or grease. Collect a small water aliquot using a clean plastic pipette (glass may scratch the glass portion of the refractometer) from a well-mixed area within the seagrass canopy keeping in mind that often the water masses within and above the vegetation may have quite different salinities. If the sampling site is not easily accessible, a bucket of water can be collected and the water aliquot can be obtained from the bucket. Place a few drops of the water onto the refractometer, close the plastic cover and expose the refractometer to sufficient light (sunlight preferred).

17.4.5 Data Collection

1. Read the salinity according to the instructions for that specific refractometer (usually the line separating a black and a white area).
2. Record the salinity as well as the location, time of the day, tidal stage and water level.
3. Wipe the glass surface with soft absorbent paper (microscopy paper is appropriate), rinse the surface with distilled water and wipe it off again.

17.4.6 Trouble Shooting

Temperature-compensated refractometers should always be used. All refractometers should be calibrated on a regular basis by adjusting the baseline (0 ‰). To do this, check if the salinity of deionized water reads 0 ‰. If not, the baseline can be easily adjusted by turning a small screw on most refractometer models. Additionally, refractometers should also be checked against other salinity measuring devices on a regular basis and sent back to the manufacturer for recalibration every 5 years or as needed.

As with temperature, salinity readings may vary with the tides. Therefore, before starting a salinity recording routine, a time series of salinity measurements at hourly intervals should be recorded over several tidal cycles. The effect of tides on the salinity at a given time of day can be followed quite easily although there may be areas where it is not straightforward (e.g., Gulf of Carpentaria, Australia where the tides change from diurnal to semi-diurnal). If the salinity is relatively constant at a given time of the day, the effect of the tides may be insignificant and salinity data can be recorded independent of tidal phase. If the salinity at a given time of day increases as tidal depth changes, tides may have an effect on salinity and, therefore, salinity data need to be collected at shorter time intervals to include several phases of the tidal cycle or at a fixed tidal phase. Alternatively, in general, measuring salinities at maximum high and low tide will usually provide the range of salinities for a given site.

17.4.7 Discussion

The salinities obtained using a refractometer should be expressed as parts per thousand (‰) but are comparable to salinities expressed as practical salinity units (psu).

Temperature and salinity data can be used to identify water masses. When these two parameters are recorded simultaneously and at relatively short time intervals (minutes to hours), an abrupt change in temperature and salinity can be used as an indication of a new

water mass entering the area where the measurements are being taken. For example, in narrow estuaries with high tidal ranges where oceanic water moves relatively far upstream during the flood and lower salinity water moves downstream during the ebb, changes in temperature and salinity can be used to identify these two water masses and their residence time at the study site.

17.5 Currents

17.5.1 Introduction

Water flow affects almost all biological, geological and chemical processes in seagrass ecosystems. For example, the pollination of seagrass flowers depends on currents and turbulence around these reproductive structures (Ackerman 1986, Verduin 1996a, Ackerman 1997); the photosynthetic rate of seagrasses depends on the thickness of the diffusive boundary layer (Koch 1994); the sedimentation rates depend on the currents and waves that are altered by the vegetation (see review, Fonseca 1996); some fauna found in seagrass beds depends on the low current environments created by the presence of the vegetation (Murphey and Fonseca 1995); and the geochemistry of the sediments inhabited by seagrasses is also affected by water flow (Koch 1999). Most seagrass-related studies could benefit from the quantification of the hydrodynamic conditions under which the experiments are taking place.

Water flow in seagrass habitats can be divided into unidirectional and oscillatory flows. Unidirectional flows (often referred to as currents) are those in which water particles tend to move in the same direction over time (usually parallel to the bottom) resulting in a net horizontal (and to a lesser extent also vertical, Nepf and Koch 1999) displacement. These unidirectional flows in marine environments are usually generated by tides. Tides can also be viewed as low frequency oscillatory flows. For more on oscillatory flows, see Section 17.6.

The ideal method to measure current velocity in situ is through a non-invasive field technique that has high temporal and spatial resolution. Unfortunately, such a technique does not exist. Instead, several invasive and some expensive and not always appropriate non-invasive techniques are available (Table 17-1).

17.5.2 Objective

Quantification of advective velocity in seagrass habitats using a simple, inexpensive and non-invasive technique: dye tracking.

17.5.3 Necessary Materials and Equipment

- Boat, canoe or kayak
- Timer or watch with seconds precision
- Gloves
- Rubber bands
- Two thin poles
- Small balloons
- Measuring tape

- Dye (rhodamine WT or fluoresceine)
- Syringes with an attached tube for sampling the water column at a certain depth (or an automated water sampler)
- Sampling vials
- Insulated box to store vials
- Fluorometer or spectrophotometer

Table 17-1. Techniques for measuring current velocity (organized in ascending order of cost).

Technique (reference)	Positive aspects	Negative aspects
Dye tracking (Worcester 1995, Rybicki et al. 1997)	Simple, inexpensive	Limited temporal and spatial resolution
Plaster balls (Komatsu and Kawai 1992, Komatsu 1996)	Simple, inexpensive	Extensive and complicated calibrations required (Porter et al. 2000)
Propeller-driven current meters	Inexpensive	Not effective in seagrass beds (Fonseca 1990)
Anemometers (Koch 1994, Koch and Gust 1999)	Small	Time consuming calibrations
Magnetic current meters (Grizzle et al. 1996, Thomas et al. 2000)	High temporal resolution; affordable	Low spatial resolution
Acoustic Doppler Velocimeter (ADV) (Verduin 1996b)	High accuracy and temporal resolution	Data collected close (< 1 cm) to boundaries (leaves, sediment) may be erroneous (Finelli et al. 1999)
Laser Doppler Velocimeter (LDV) (Gambi et al. 1990)	High accuracy and temporal resolution	Expensive
Particle Image Velocimeter (PIV)	High accuracy, temporal and spatial resolution	Expensive; seagrass leaves create zones in which measurements can not be taken (shading of the light sheath)

17.5.4 Methods

Mix the dye with 100 to 500 ml of water from the site (the temperature and the salinity of the dyed water need to be the same as that of the water at the study site to achieve neutral buoyancy). Fluorescein at a concentration of 3 g per liter of seawater or a 20% rhodamine WT solution allow the dyed water mass to be clearly tracked. The use of gloves is recommended when using these dyes. Place the dyed water in a balloon and close it with an adjustable pinch clamp. Choose the site (above/within canopy or unvegetated) where the advective velocity is to be quantified (usually expressed as a certain height above the bottom). Firmly attach the balloon to a narrow pole (the narrower the pole, the less the water flow will be affected by the pole) at the chosen height above the bottom using rubber bands.

Determine the direction of the flow by observing the flow around the pole and the trajectory of particles in the water. If needed, sediment grains can be released into the water to visualize the flow direction but make sure there is no obstruction in the flow. Install a sampling pole 30 to 50 m downstream from the first pole (Figure 17-1). If the seagrass bed is smaller than this, the distance between the poles can be reduced. Attach the sampling tube

(connected to the syringe or automated water sampler) to the sampling pole such that the opening is at the upstream side of the pole and at the same height above the sediment as the balloon. The syringe should be positioned such that the individual taking the samples (possibly from a boat) can easily manipulate it. An automated water sampler can be used instead of the syringe.

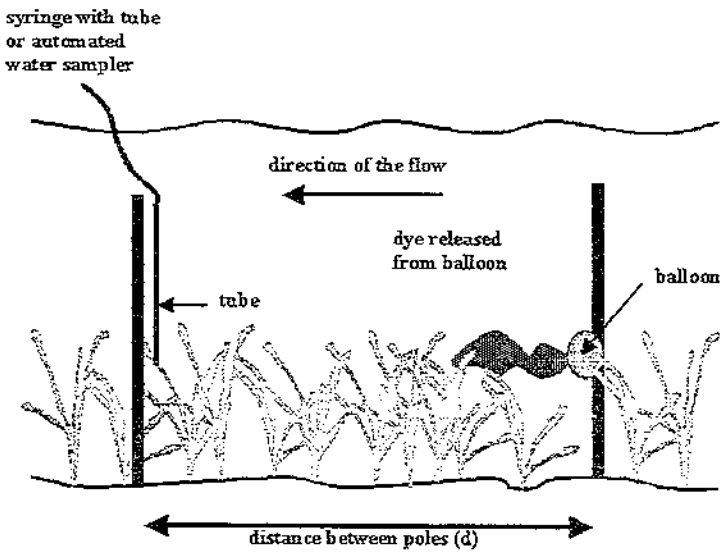

Figure 17-1. Example of a set-up to quantify advective velocity using the dye-tracking technique.

17.5.5 Sample and Data Collection

1. One individual releases the dye to form a compact (smaller than 1 m in diameter) blob. Record the time (in seconds) as well as the distance between the poles.
2. Another individual starts collecting water samples via the syringe at the second pole (as much as needed for the fluorometer or spectrophotometer) at regular time intervals. The water sampling time interval will be determined by the magnitude of the current. For example, if the poles are 50 m apart and the flow is approximately 5 cm s^{-1}, the dye will take 16 minutes and 40 seconds to reach the sampling pole. Because water samples are expected to be collected until the dye has passed the pole, it is recommended that the sampling period be twice as long as it takes for the dye to move from one pole to the other (in the above example, 33 minutes and 20 seconds). A minimum of 10 water samples should be available, therefore, in the above example water samples are collected at 3 min intervals. Note that the tube through which the water samples are collected needs to be flushed with water with no trace of dye or with air after each water sample is retrieved.

3. Place each water sample in a labeled vial, indicating time of collection, and store them in a cool dark place until they reach the lab and are processed.
4. Analyze the samples in a fluorometer or spectrophotometer and plot a concentration time series. It should resemble a bell shaped curve where the concentration (C_i) changes over time (T_i). Note that the width of the base of the curve depends on the turbulence in the area. The wider the base, the more turbulent the site.
5. Calculate mean advective velocity (U) by first calculating the arrival time (T) of the dye at the sampling pole using the following equation:

$$T = \frac{\sum_{i=1}^{N} T_i C_i dt}{\sum_{i=1}^{N} C_i dt}$$

where N is the number of measurements between the arrival time of the leading edge and the arrival time of the trailing edge of the dye; T_i is the *i*th minute since the release of the dye; C_i is the observed dye concentration at T_i and *dt* is the amount of time between successive measurements.

6. Then calculate the mean advective velocity (U) in cm s^{-1} or m s^{-1} using:

$$U = d/T$$

where d is the distance between the dye injection site (pole with balloon) and the sampling site (Figure 17-1).

The syringe collection method is appropriate when a fluorometer or spectrophotometer is available. Alternatively, instead of collecting water samples to determine the velocity of the dyed water mass, high-frequency photographs of an area through which the dye is moving can also be used to quantify water flow. In this case, a camera should be mounted at a fixed point perpendicular to the flow, 2 to 5 m away from the dye track, above or in the water depending on the depth of the water column and the site of the dye release. Approximately ten pictures should be taken during the time the dye passes through the viewing field. The time each picture is taken is recorded to determine the speed at which the water is moving. Additionally, reference poles in the viewing field may help to determine the distance the dye blob traveled. Small dye blobs may be easier to track than large ones.

When using photography to quantify advective velocity in seagrass habitats, the distance the dye blob moved is divided by the time it took for the center of the dye blob to move from position 1 to position 2 (Figure 17-2) and then averaging all the velocities obtained from tracking that dye blob (Worcester 1995).

17.5.6 Trouble Shooting and Hints

This method relies on the displacement of the dye and, therefore, needs to be performed under steady flow conditions, i.e., during an ebb or a flood tide but not during slack water. Best results are achieved when the dye is squeezed from the balloon at approximately the same rate as the water is flowing (to avoid increasing local turbulence) but release of the dye should not last more than a minute (to create a well defined blob).

It is suggested that the dye-tracking procedure be repeated several times and that the average of several runs be used. As the results vary with a variety of parameters, it is important to also record the water depth, canopy height, percentage of the water column occupied by the vegetation, seagrass density, size and patchiness of the seagrass bed, tidal phase, wind intensity and direction, and waves if possible (Section 17.6).

Although the dye used in these experiments is usually biodegradable and non-toxic, it may be advisable to check with the local authorities if a permit is required to release dye in local seagrass beds. Oranges (or other fruits and vegetables) can be used as surface water tracers.

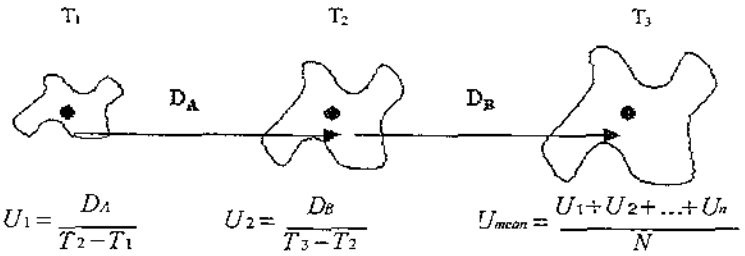

Figure 17-2. An example of how sequential photographs of a moving dye blob can be used to quantify advective velocity (U) in seagrass habitats. T_1, T_2, T_3 represent the time (T). D_A, D_B represent the distance traveled by the center of the dye blob between time T_1 and T_2 and T_2 and T_3, respectively. N represents the number of samples used in the calculations.

17.5.7 Discussion

Water flow affects almost all processes occurring in seagrass beds, from the smallest (physiological and molecular) to the largest (meadow-wide). Current velocities in seagrass habitats have been observed to be as high as 180 cm s^{-1} (Phillips 1974) but within the vegetation, water flow is commonly less than 10 cm s^{-1} (Fonseca and Kenworthy 1987, Grizzle et al. 1996, Koch 1996). When quantifying water flow at the study site even when the focus of the work is not directly related to this parameter, a new insight can be gained.

It is recommended that shoot density, canopy height and any other obstruction to water flow (macroalgae, gorgonians, clams, etc.) be quantified at the study site. This may aid in the later interpretation of the results. The dye tracking technique only allows for estimations of average flows over relatively broad spatial scales. Therefore, other techniques may be needed to resolve hydrodynamic processes at smaller scales.

17.6 Waves

17.6.1 Introduction

Waves in seagrass habitats occur at a variety of frequencies. Some of the lower frequency waves with periods (time interval between two successive wave peaks or troughs passing a fixed point) of hours, such as tides, are caused by gravitational attraction between the earth, moon and sun. In contrast, most high frequency waves (periods of seconds to minutes) are the result of wind blowing over the water surface and are, therefore, called wind waves. Swell (waves generated far away from the area where they are observed) generally have a longer period and wave length than waves generated locally. Based on the local dominance of wave periodicity, seagrass habitats may be classified into tide-dominated, wave-dominated or mixed regimes. In the wave-dominated habitats, seagrass leaves tend to flap back and forth with the oscillatory motion of the waves while in tide-dominated habitats, seagrass leaves tend to bend in the direction of the tidal flows. In mixed habitats, seagrass leaves have a complex motion resembling a constant flapping motion but only in the direction of the flow.

Waves are not only characterised by their frequency but also by their height, length (L), amplitude, period, and speed. Additionally, waves are divided into deep, intermediate and shallow water waves. Deep water waves are those travelling over depths larger than L/2; shallow water waves are those where depths are less than L/20 and intermediate waves are those travelling over depths between L/2 and L/20. For deep waves, the orbits of water molecules and particles in the water are circular and are only affected by the wavelength. In transitional waves, the path of particles in the water follows an oval path due to the distortion of the orbits by friction from the seafloor. In shallow water waves the orbits of particles are flattened so much that their oscillatory motion becomes nearly horizontal (back and forth motion only). These oscillatory flows control mixing of particulate and dissolved matter within seagrass meadows and the water column above them (Koch and Gust 1999).

The simplest and most inexpensive way to measure waves is to make a visual estimation looking at or videotaping the sea surface (Morgan 2000). For example, visual observations of the surface displacement against a fixed vertical scale can be used to estimate wave height. The wave period can be estimated from the time it takes two subsequent crests or troughs to pass a fixed point and the wave height can be estimated from the vertical distance between troughs and crests. These estimates, in turn, may be used in calculations of hydrodynamic forces which are experienced by organisms (Denny 1995) like seagrasses. This method of wave visualisation can be easily applied where wave height is large and wave frequency is low (oceanic areas and coastal areas with long fetches). In areas where wave height is small (< 1 cm) and wave frequency is high (most coastal areas), it may not be a simple task. A special video player that allows for individual frame analysis may be needed (expensive) and the time to obtain a single wave time-series may be prohibitive. As a result, statistically relevant parameters like significant wave height (average height of the highest one-third of all waves occurring in a particular time period) and dominant wave frequency can not be easily obtained from these data. Therefore, to assure that data obtained over a broad geographical range can be easily compared between sites and with the oceanographic literature, the use of pressure transducers connected to data loggers mounted below the depth of the deepest wave trough or

at the seabed is recommended. The wave record obtained from pressure transducers is based on the principle that the hydrostatic pressure below the surface varies periodically as the depth of water varies due to the passage of waves thus creating a continuous record of pressure against time.

17.6.2 Objective

To characterise waves in seagrass habitats using a pressure transducer connected to a data logger.

17.6.3 Necessary Materials and Equipment

- Pole
- Tide Table
- Computer
- Pressure transducer (www.trans-metrics.com) and data logger (www.coastal-usa.com)

17.6.4 Methods

The first step in collecting wave data in a seagrass bed using a pressure sensor is programming the data logger. Two important parameters to be considered are the duration of the deployment and the frequency at which the data will be recorded. The duration of the deployment must be long enough to obtain a data record statistically sufficient to cover the wave motion regime. This is a function of the bottom topography (slope of the seagrass habitat) and the predominant wave motion regime of the study area (oceanic, coastal). This period is recommended to be 10 minutes or longer. As the tidal regime can affect the waves, especially in shallow seagrass habitats (at low tide the waves may be higher than at high tide and at high tide, seagrasses may attenuate waves less than at low tide), it is recommended that a deployment cover at least one tidal cycle, preferably three. Therefore, 10 minute bursts every hour over a tidal cycle is the minimal recommended deployment duration to characterise waves in a seagrass habitat.

The frequency at which each data point is recorded depends on the wave frequency. For high frequency waves (coastal areas), waves are recorded at no less than 5Hz (5 times per second). If possible, they are recorded at a 25 Hz frequency. For low frequency waves (oceanic areas), waves may be recorded at lower frequencies. Once the data logger has been programmed, the pressure transducer can be deployed at the study site. The continuously recording pressure sensor is installed on a fixed pole or at the sediment surface. It is important to note that the pressure transducer needs to be installed in such a way that it does not move or tremble as this would be recorded as "water motion". Once the instrument is deployed, it can usually be left unattended until the time it is recovered. At that point the data can be retrieved and analysed.

17.6.5 Data Collection

1. Deploy the pressure transducer on a pole or at the sediment surface and record the time and date the measurements are beginning. Record climatic conditions during the deployment (if possible). These data are often available from nearby airports.
2. Retrieve the pressure transducer from the field site noting the time and date.
3. Offload the data.
4. Analyse the data.

The output of the water height over time (i.e., wave time-series) can be analyzed by simply determining the average wave height (distance between trough and crest) and wave period (time between troughs or crests). Because the surface of the sea typically possesses a disordered, even chaotic appearance, statistical methods are recommended to characterize waves. Fast Fourier Transformation (FFT) is often used for such analysis of wave data. A common use of FFT is to find the dominant wave frequency and the significant wave height buried in a noisy time domain signal. FFT routines are available in data analysis programs (www.mathworks.com) as well as in software packages sold by wave gauge (pressure transducer) manufacturers. Methods to calculate and plot FFT's are described by Little and Shure (1988).

17.6.6 Trouble Shooting and Hints

If after processing the data, wave frequency appears strange (higher or lower than normally seen in the natural environment), the pressure sensor may have been attached to a vibrating pole or tumbling along the bottom. If a dominant wave frequency can not be identified by FFT (wave spectra did not include the wave peak), the frequency of data collection may have been too low.

In certain zones of wave action, such as the surf zone where conditions may be extremely rough it may not be possible to deploy pressure transducers. The very strong currents and energy from breaking waves are, however, very important in understanding the ecology of seagrass systems. Dynamometers are useful in this case to record maximum wave forces (Bell and Denny 1998, Castilla et al. 1998).

17.6.7 Discussion

It is recommended that the following parameters also be recorded concomitant with wave data: wind speed and direction, wave direction and tidal conditions. Wind data may be available from nearby airports while wave and tides may be obtained visually and from tide tables, respectively.

The wave measuring methods described above (visual technique and pressure sensor deployment) have the disadvantage of providing information at one fixed point only. For more complete information at the landscape scale, wave models are often used. A range of numerical deep water wave models exist (Komen et al. 1995). These wave models, however, predict wave parameters in the absence of vegetation and may not reflect the conditions in

seagrass habitats. Other hydrodynamic models, namely for shallow unvegetated coastal areas predict shallow water waves (Backhaus 1985). Unfortunately, at present no wave models exist for vegetated shallow coastal regions.

17.7 Turbulence

17.7.1 Introduction

Turbulence consists of temporally and spatially irregular water motion superimposed on the larger flow pattern (unidirectional and oscillatory flows). It forms at boundaries like the sediment surface or the surface of seagrass leaves (Gambi et al. 1990, Koch 1996, Koch and Gust 1999). It is then transferred from larger to smaller scales or eddie sizes (Anderson and Charters 1982, Gambi et al. 1990, Ackerman and Okubo 1993, Koch 1996) and ultimately dissipates in the form of heat. Turbulence increases with plant density and current velocity (Dunn et al. 1996) although, when currents are so strong that the vegetation bends over, the water flow is redirected over the vegetation (skimming flows) and turbulence levels within the canopy may decrease (Nepf 1999). Turbulence has the potential to be of extreme ecological importance in seagrass habitats as it affects the mass transfer of nutrients and carbon in the water (Sanford 1997) as well as the dispersion of particles such as pollen, larvae, seeds and spores (Ackerman 1997 1998).

Turbulence is a relatively complex subject. Books written for biologists like those by Denny (1988), Vogel (1994) and Campbell and Norman (1998) may be a first step in understanding turbulence and can be followed by other books on hydrodynamics like those by Tennekes and Lumley (1972) and Kundu (1990).

As turbulence is a process characterized by high spatial and temporal changes in water motion, high-frequency measurements (several times per second) are necessary to quantify turbulent energy in seagrass habitats. A variety of instruments are available to quantify turbulence at the appropriate time scales but they are expensive and often provide erroneous data due to interference with the seagrass leaves (Table 17-1).

An indicator of turbulence (turbulent mixing coefficient) can easily and inexpensively be described using the dye-tracking technique (Worcester 1995). This method is based on the principle that when there is no flow, the dye will only dissipate via diffusion while, the more turbulent an environment, the faster a dye blob tends to dissipate. As for currents, this technique has relatively low spatial resolution and is not appropriate for small scale studies like the turbulence created by seagrass flowers and epiphytes but can be used to describe turbulent mixing in seagrass habitats. These data are particularly valuable for comparative studies in beds of different density, patchiness, species and over a range of hydrodynamic conditions.

17.7.2 Objective

Characterization of turbulent mixing in seagrass habitats using the dye dissipation technique.

17.7.3 Necessary Materials and Equipment

- Boat, canoe or kayak
- Stop watch or high precision (seconds) watch
- Measuring tape
- Two thin reference poles
- Small balloons
- Pole to support the balloon
- Dye (rhodamine WT or fluoresceine)
- 35 mm camera and Sea-going tripod for camera

17.7.4 Methods

Mix the fluoresceine (3 g l^{-1} seawater) or rhodamine WT (20% seawater solution) dye with 100 to 500 ml of water from the site (the temperature and the salinity of the dyed water need to be the same as that of the water at the study site to achieve neutral buoyancy). Place the dyed water in a small balloon and close it. Choose the site (above or within canopy) where the turbulent mixing coefficient is to be quantified (usually expressed as a certain distance from the bottom). Firmly attach the balloon to a pole at the chosen height above the bottom using rubber bands.

Determine the direction of the flow according to the method described under Section 17.5.4. Position the camera perpendicular to the flow such that the viewing field begins close to the pole with the balloon and continues in the direction of the flow. Install two reference poles (the narrower the pole, the less turbulence will be affected by the pole) within the viewing area of the camera and measure the distance between them using the measuring tape.

17.7.5 Sample and Data Collection

1. One individual pierces or cuts the balloon to slowly release the dye to form a small (< 1 m in diameter) blob.
2. Another individual starts taking pictures at regular time intervals without moving the camera. The time interval between pictures will be determined by the magnitude of the current and turbulence. For example, if the viewing area of the camera covers a 10 m length and the flow is approximately 5 cm s^{-1}, the dye should take 200 seconds to reach the end of the viewing area. As approximately 10 pictures should be available during that time period, for the above example, photos should be taken at 20 sec intervals. Note the time each picture is taken.
3. Repeat the experiment at least 2 more times.
4. Develop the pictures.
5. Quantify the rate of spread of the dye blob over time by measuring the length (L) and width (W) of the blob in each picture (use the reference poles for consistency in distances) as in Figure 17-3.
6. Calculate the slope of each line (width and length, Figure 17-3). These are the turbulent mixing coefficients in the direction of the flow (K_L); perpendicular to the flow (K_W).

Figure 17-
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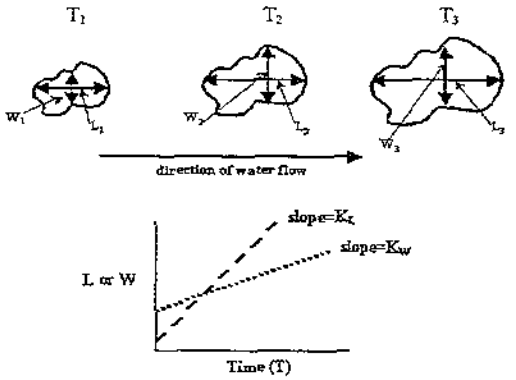

Figure 17-3. An example of how sequential photographs of a moving dye blob can be used to determine turbulent mixing coefficients in the direction of the flow (K_L) as well as perpendicular to the flow (K_W) by measuring the evolution of the length (L) and width (W) of the blob over time (T).

17.7.6 Trouble Shooting and Hints

It is relatively easy to use the dye-tracking technique at the water surface. When turbulence is to be quantified within dense seagrass beds or relatively deep, it may be necessary to use an underwater camera. The tidal level can also be used to the investigator's advantage. One experiment could be run during ebb while the water level is relatively high and the vegetation occupies only a fraction of the water column therefore allowing for the quantification of turbulence in the water column well above the seagrass bed (using above water photography). Another experiment could be run during the flood while the water level is relatively low and the vegetation occupies the entire water column therefore allowing for the quantification of turbulence within the vegetation while using above water photography.

As the results/turbulence can vary with a variety of parameters, it is important to also record: water depth, canopy height, percentage of the water column occupied by the vegetation, seagrass density, size and patchiness of the seagrass bed, tidal phase, wind intensity and direction as well as waves (if possible).

The disadvantage of the dye-tracking technique is that it has poor spatial and temporal resolution. Therefore, when smaller scale questions are asked (for example: pollination or turbulence generated by epiphytes), more sophisticated techniques (LDV, PIV) need to be employed.

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