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Making Waves in the Classroom – Engaging Students in STEM through Hands-on Coastal Oceanography and Engineering

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Abstract

A high school Science, Technology, Engineering and Mathematics (STEM) program was initiated to engage students in coastal processes and engineering concepts. Fourteen portable wave flumes were designed, fabricated, and delivered to high schools along the East Coast of the United States from New Jersey to Florida. The ~5 m long flume consists of a motor-controlled wave paddle at one end and a sediment-surrogate beach at the other end for hands-on activities for coastal dynamics. Sensors for measuring water level and fluid velocity and education modules ranging from basic wave concepts to applications such as beach nourishment are provided to teachers to assist in education delivery. Pre- and post-module worksheets and overall program surveys are used as assessment instruments to gauge effectiveness of the program. The student and teacher assessment results indicate that the portable wave flumes and associated modules were successful in helping students understand coastal processes in an engaging and hands-on manner. All teachers surveyed indicated that they plan to use the flume again. Modifications in the future may include creating lesson plans with more open-ended questions to encourage student exploration, decreasing the apparatus footprint, and using an actuator-controlled wave paddle for irregular wave forcing.

1. Introduction

The disciplines of Science, Technology, Engineering, and Mathematics (STEM) drive discovery and innovation that are important for economic prosperity and national security, especially in the

21st century where the pace of innovation is accelerating (Committee on STEM Education of the National Science & Technology Council, 2018). Unfortunately, in the United States (US), high school students struggle in STEM. The National Assessment of Educational Progress reported in 2019 that only 24% of US 12th grade students reach or exceed the proficient level in mathematics and only 22% reach or exceed the proficient level in science (National Assessment of Educational Progress (NAEP), 2019). The lack of proficiency appears to be exacerbated in higher education with the 2020 National Science Board Science and Engineering Indicators reporting only roughly 6% of all Bachelor's degrees are award in engineering-related fields (National Science Board, 2020). As indicated by these findings, it is imperative that student performance in STEM areas be improved by developing techniques that allow inquiry-based, creative learning to inspire, engage, and motivate students to excel in STEM disciplines.

There is a trend nationally for increased STEM content in the high school curriculum. Attention in the US is being given to the development of STEM students through aspects such as Project Lead the Way (Project Lead The Way, Inc., n.d.) and in National Science Education Standards (NSES) (National Research Council, 1996) and Next Generation Science Standards (NGSS) (Achieve, Inc., 2013). NSES and NGSS focus on inquiry-based learning, engineering design and building science-related skills. Full inquiry requires formulating a question, completing an investigation, using data to answer the question, and presenting the results to others (Bell et al., 2010).

This paper presents a new inquiry-based STEM learning experience, **Making Waves in the Classroom**, for high school students using portable wave flumes. Use of the wave flume allows for full inquiry while addressing NGSS standards including, but not limited to, waves on water and wave interaction with matter (HS-PS4), forces and interactions (HS-PS2), and using mathematical and computational thinking in analyzing geoscience data to make the claim that one change to Earth's surface can create feedbacks that cause changes to other Earth systems (HS-ESS2) (Achieve, Inc., 2013).

Students were engaged in inquiry-based, “joy of discovery”, creative learning to inspire, engage, and motivate them to excel in STEM disciplines centered on coastal oceanography and coastal engineering topics. Such topics include sustainability of coastal communities in the face of sea level rise, storm events, and tsunami. Students developed an understanding of concepts such as wave propagation, wave period/frequency, wave energy, wave breaking, sediment transport, beach erosion, and beach nourishment. Students used these concepts to learn/enhance STEM skills related to critical thinking, problem solving, data acquisition and analysis, and to engage in global considerations of engineering. Provided materials, and supplemental materials from teachers, helped to link key concepts from coastal processes to processes in other fields. For example, water wave propagation was related to optics, standing and propagating waves on a string tethered at one end, and even the “wave” that fans initiate in stadiums. Sediment related examples were compared to transport in riverine environments and the potential for erosion or deposition in different areas of a river system.

The program was initially targeted to high schools along the east coast of the US (Figure 1) encompassing a range of socio-economic settings: rural, urban, large, small, public, private, and charter schools. All wave flume plans, description, education modules, and solutions are provided at http://sites.udel.edu/jpuleo (links under the outreach tab; (Puleo, 2019)) in an effort to encourage widespread usage.

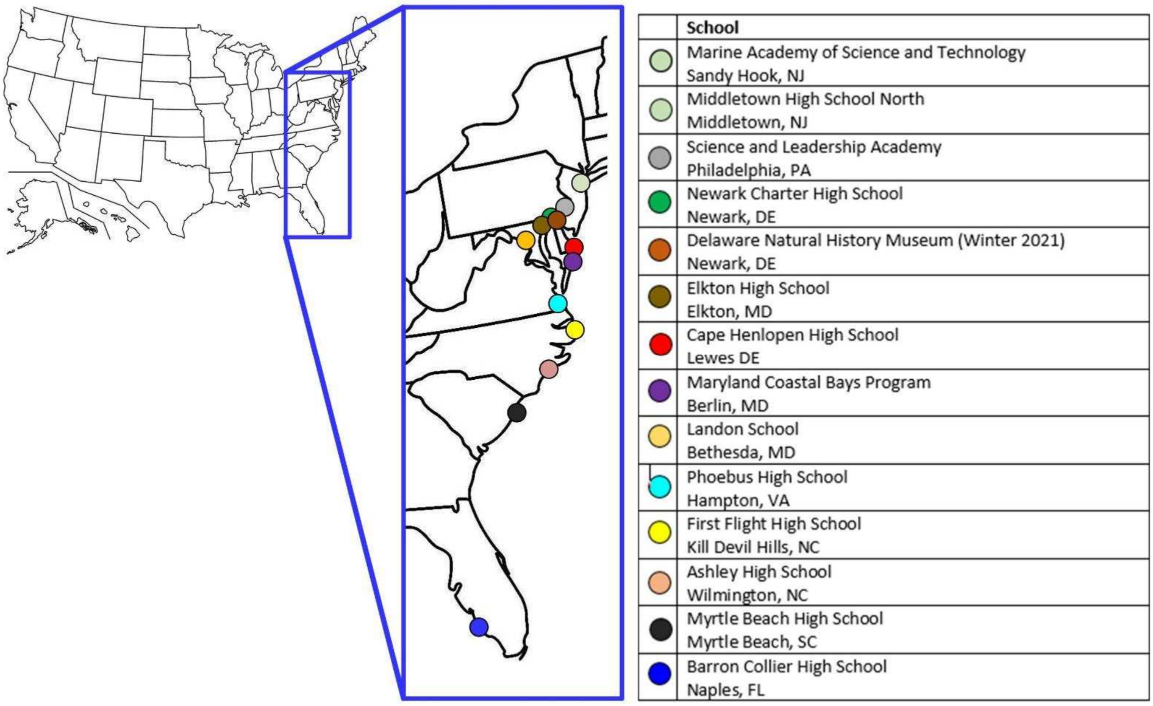


Figure 1. Map showing the geographic distribution of high schools and other agencies involved in the Making Waves in the Classroom program. Each high school / agency is color-coded to the filled circles on the map.

2. Wave Flume Apparatus

The flume consists of two 2.44 m (8 ft) sections of 1.9 cm (3/4”) optical-quality acrylic that are joined in the center using draw clasps to form a 4.88 m (16 ft) long flume (Figure 2). The flume is 0.35 m (1 ft) tall and 0.15 m (0.5 ft) wide. The portable flume can be set up in under 45 minutes by two people and easily transported in the back of a pickup truck, which simplifies delivery. A flap-type wave paddle is hinged at the offshore end of the flume and attached using a linkage arm to an aluminum wheel. The wheel is attached to a direct current (DC) motor. Slots on the wheel allow the stroke of the flap to be altered. A variable DC speed controller is used to alter the speed of paddle motion and hence wave frequency. The motor and controller are housed in a plywood mount for stability. The flume rests on two 0.91 m (3 ft) high scaffolding sections, allowing students to easily work with the apparatus. At one end of the flume, a solid acrylic slope can be installed if only wave motion is of interest. Otherwise, Acetal beads (diameter ~ 3.5 mm) are used as a sediment surrogate to create a “natural” beach that evolves quickly (Figure 3). Acetal is chosen for two reasons: 1) Acetal is non-abrasive and does not scratch the acrylic; and 2) the specific gravity of Acetal is 1.42, roughly half that of sand, making it easily mobile under the scaled laboratory conditions. The pedagogical benefit of enhanced mobility is that beach changes are observed in just a few minutes, allowing students to immediately comprehend the resulting effect of changing the stroke length, paddle speed, water level, or initial morphology conditions. A local cross-shore coordinate system along the bottom of the flume is defined for positioning. Morphological changes can be quantified pre- and post-wave conditions using pin striping tape or a grease marker and a ruler (Figure 3).

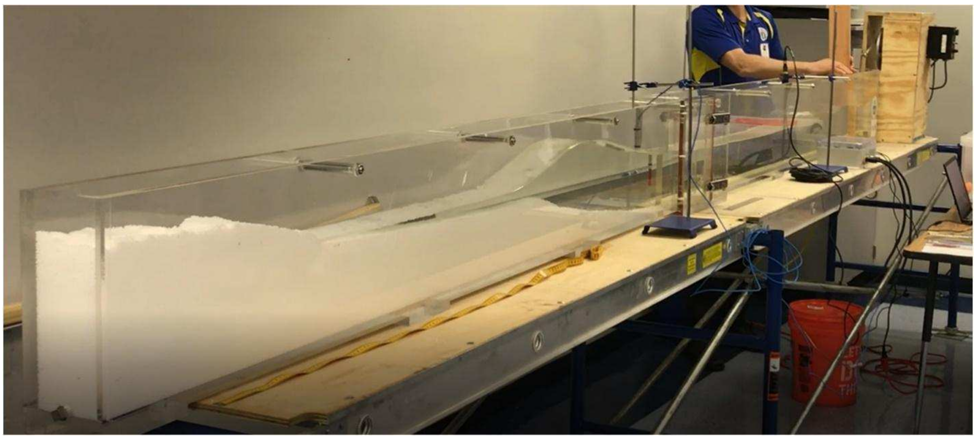


Figure 2. Wave flume used in the Making Waves in the Classroom Project.

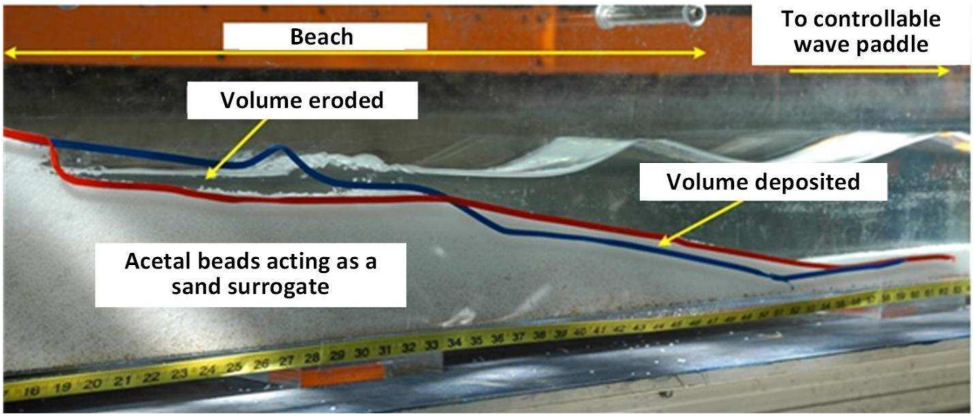


Figure 3. Image of wave flume showing beach using Acetal beads. Colored tape placed on the flume wall by students quantifies the change from a "summer" (blue) to "winter" (red) beach profile.

Sensors and data logging capabilities were incorporated into the system to provide data capture and analysis opportunities for students. Vernier data logging equipment was chosen because it is a well-known supplier of data loggers for high school science laboratories and is inexpensive, however, Vernier does not supply the needed sensors for the flume. The data loggers do have the capability to record voltage signals from third party sensors. Two sensors were used with the wave flume:

1. <u>Banner Ultrasonic Distance Meter (Figure 4A)</u>: The distance meter (current version with model number: S18UIAQ) with Euro-style quick disconnect (model number: MQDEC2-530) measures distance over a range of 30 to 300 mm. The current version requires a resistor (470 Ω) in the current loop to change to voltage for data logger recording. The sensor measures time of flight for sound waves and is clamped into a lab stand and oriented downward above the flume roughly centered between the flume walls. The sensor is used to record the free surface profile of waves propagating landward.

2. Omni Instruments Impellor Current Meter (Figure 4B): The current meter (MiniWater6 Micro, model number: MIWA0611) measures fluid speed from 0.04 to 5 m/s with a 0 – 1 V output. The sensor is first taped or cable tied to a narrow diameter stainless steel tube and then clamped into a lab stand. The sensor is meant to generally measure higher flow speeds in the flume and cannot differentiate flow direction. Thus, the sensor is largely used to identify flow magnitudes at different cross-shore positions and/or water depths.

The data logger and sensors are wired into an electronics enclosure (Figure 4C) such that users need only connect the provided power supply to a wall outlet and the USB cable to the supplied laptop computer. Real-time data are viewed through the Vernier software while also being saved as a CSV file. Data can be copy/pasted into Microsoft Excel where provided spreadsheets generate plots and perform calculations.

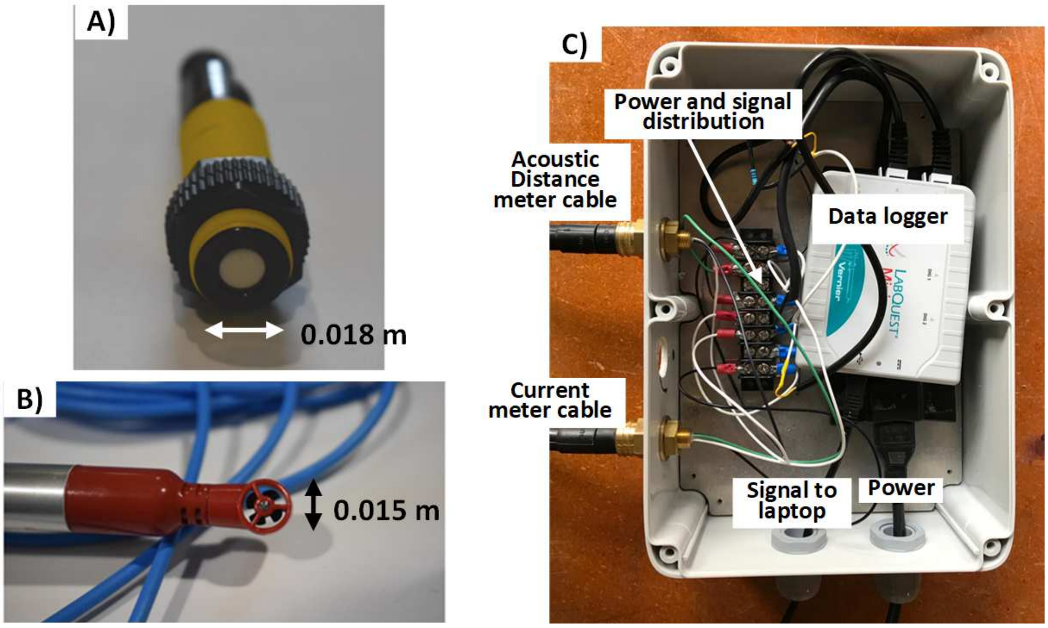


Figure 4. Pictures of acoustic distance meter, current meter, and electronics enclosure.

3. Wave Flume Modules

Modules with grade-appropriate science and mathematics activities based on coastal oceanography and engineering were developed for use with the portable wave flume (Table 1). The modules span from basic physics to natural hazards to applied engineering. Many modules come with a pre-activity questionnaire and post-activity worksheet as an assessment tool for the program. For brevity, only three modules are described here.

Table 1. STEM modules for the Making Waves in the Classroom program.

Module 1: What is a wave? Learning outcome: Describe what a wave is in coastal or other settings	Module 8: Beach profiles and basic theory Learning outcome: Explain what a beach profile is and measurements methods
Module 2: Wave parameters Learning outcome: Describe and calculate wave parameters including frequency, period, amplitude and wavelength	Module 9: Application—beach slope and slope predictions Learning outcome: Examine beach slope and compare to basic theory
Module 3: Deep vs. shallow water Learning outcome: Distinguish between deep and shallow water waves	Module 10: Beach erosion Learning outcome: Describe beach erosion and calculate volumetric changes
Module 4: Wave speed Learning outcome: Calculate wave phase speed based on wavelength, period and/or depth	Module 11: Application—beach nourishment Learning outcome: Describe what beach nourishment is and experiment with a "nourishment" in the flume
Module 5: Particle trajectories Learning outcome: Describe how particle trajectories change with relative depth	Module 12: Sea level rise & effect on beaches Learning outcome: Explain causes of sea level rise, experiment with sea level rise test in the flume and interpret the effect on the beach profile
Module 6: Wave energy Learning outcome: Analyze wave energy based on wave height	Module 13: Application—Protecting the beach Learning outcome: Describe difference between soft and hard solution for protecting the beach, test a hard solution in the flume and interpret the effect on the beach profile
Module 7: Tsunami Learning outcome: Describe causes of tsunamis and typical tsunami wave speed	

3.1. Description of "Module 2: Wave parameters"

It is most straightforward to examine an idealized small amplitude deep water wave that has a sinusoidal shape (Figure 5). The learning objective of this module is to familiarize students with the different parts of the wave form and parameters that are attributed to the wave form.

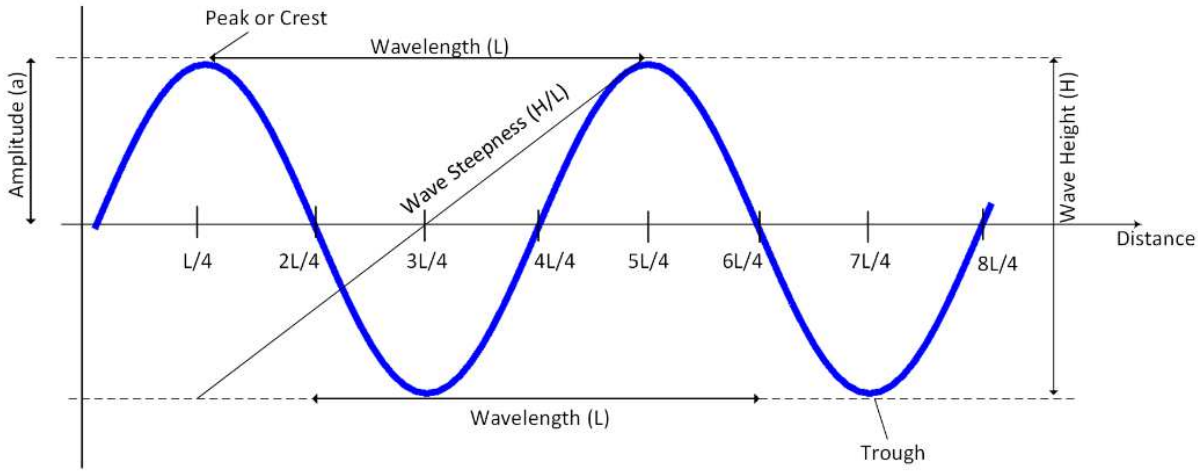


Figure 5. Image showing the parts and parameters of a sinusoidal wave train.

The top of a wave shape is referred to as the wave peak or crest. The bottom is referred to as the trough. The distance between these locations is known as the wave height (*H*). The wave amplitude (*a*) is half the wave height and is the distance from the mean water level to either the crest or trough. The wavelength (*L*) is the distance between two successive peaks or troughs (or two other corresponding portions of the wave as shown in Figure 5). The wave steepness (*H*/*L*) is the ratio of the wave height to wavelength.

Additional parameters can be identified if the horizontal axis in Figure 5 is changed from distance to time. The wave period (*T*) is the time it takes for a wave to complete a single cycle. The wave frequency (*f*) refers to how often a wave peak or trough occurs. Frequency is usually given in units of Hertz (Hz) described as cycles per second. Period and frequency are inverses of each other, as shown in the equation (1).

$$T = \frac{1}{f} \ and \ f = \frac{1}{T}. \tag{1}$$

The wave shape in the open ocean (covered in "Module 3: Deep vs shallow water") can be estimated as sinusoidal. Thus, it can be described as:

$$\eta = a * sin(k * x - \sigma * t), \tag{2}$$

where η is the free surface, x is the distance, t is the time, k is a parameter called the radial wave number (or just wave number) and defined as $\frac{2\pi}{L}$, and σ is a parameter call the angular frequency, similar to before, but defined as $\frac{2\pi}{T}$ instead of $\frac{1}{T}$. Equation (2) is helpful because it allows identification of the elevation of the free surface at any space-time location. The most straightforward way to use equation (2) is to fix either time or space. That is, set $t = 0$ or $x = 0$. For example, setting $t = 0$ means one is observing a single snapshot of the wave shape (analogous to taking a photo of the side of the flume with a camera). In contrast, setting $x = 0$ means the person (or sensor) is observing the change in water level over time at a particular fixed location in space. Numerous examples are provided in the wave flume module with one example shown here.

Example: Determine the free surface elevation of a wave with amplitude (a) of 1.3 m and a wavelength (L) of 100 m at a distance 452 m from the origin.

$$\eta = 1.3 * \ sin\left(\frac{2\pi}{100} * 452\right) = -0.16 \ m. \tag{3}$$

Students used the wave flume to investigate wave parameters following content delivery. Students were asked to devise a way to measure the wave period/frequency/angular frequency with the wave paddle speed dial at two different settings but to not use sensors initially. Note, that this part of the exercise can be done using a stopwatch with a student timing the passage of the wave crest, for example, past a fixed location. Students then postulated why there was a difference in wave periods with the paddle at two settings and were asked to estimate the wave period and frequency for a wave with the paddle setting halfway between the two settings tested previously. They then adjusted the paddle and check their result.

The acoustic distance meter was used to extract information on wave parameters. Students recorded the free surface elevation some distance from the wave paddle and identified that location with a temporary horizontal position of $x = 0$ m. Data from the logger was imported into the provided spreadsheet to estimate wave height, amplitude, period, and angular frequency (Figure 6). Students were asked to identify a time when the data first crossed the x-axis so the time series could be shifted horizontally. The graph then updated to show the measured free surface profile and the theoretical deep water (sinusoidal) profile based on the estimated wave parameters. Students were asked to assess how similar the curves were and postulate why any differences may exist. Note again that differences in wave shape (e.g. shallow vs. deep water) are provided in the subsequent module.

Time (s)	Free Surface Data (m)	Data
		0.000
0	0.008	-0.010
0.1	0.002	-0.016
0.2	-0.005	-0.015
0.3	-0.005	-0.007
0.4	-0.005	0.004
0.5	-0.005	0.013
0.6	0.002	0.016
0.7	0.012	0.012
0.8	0.016	0.002
0.9	0.011	-0.009
1	0.005	-0.016
1.1	-0.002	-0.016
1.2	-0.005	-0.009
1.3	-0.005	0.002
1.4	-0.005	0.012
1.5	-0.004	0.016
1.6	0.009	0.013
1.7	0.015	0.004
1.8	0.014	-0.007
1.9	0.007	-0.015
2	0.002	-0.016

Enter Amplitude (m) here	0.0165
Enter Period (s) here	0.92
Angular Frequency (s^{-1})	6.830

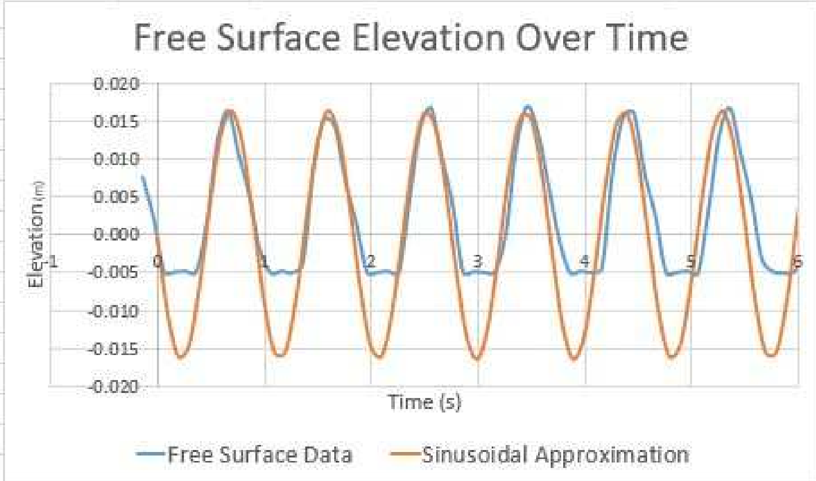


Figure 6. Screenshot of spreadsheet provided for Module 2.

3.2. Description of "Module 10: Beach erosion"

The classic example of beach change is related to "summer" and "winter" beach profiles (Shepard, 1950). During "summer" conditions, waves tend to have small amplitudes and perhaps a relatively long period. Conversely, during "winter" conditions, waves tend to have larger amplitude and perhaps relatively shorter periods for locally generated storms. These variations in wave climate play a role in beach change. In the "summer" case, the beach tends to accrete forming a berm and landward sloping back beach area. In the "winter" case, the berm tends to erode, and sediment is deposited offshore. These processes can be demonstrated easily in the wave flume and are visible in Figure 3 (change occurred in less than 5 minutes). Demonstrating these processes gives students the opportunity to describe qualitatively what they observe and relate their observations to the wave forcing conditions before performing any quantitative analysis.

Engineers, scientists, municipality managers, and insurance agencies (among others) have an interest in how the beach changes over time as it can affect property and infrastructure loss. The change of most interest/concern is beach erosion where sand is removed from the landward portion of the beach profile and carried offshore or alongshore. Often, this sand or some fraction of it will return to the beach under calmer conditions, but that is not always the case. Beach erosion processes can be studied by measuring the profile elevation before and after erosive conditions (e.g., storm) occur. The difference in profile elevation at each cross-shore position provides the local change (Figure 7). Integrating those changes across the profile yields the total volume change in the beach profile. Students were given direction on how to "survey" the beach profile using a local coordinate system and were informed as to the similarities to standard surveying using GPS technology, and laser range finding or stadia rod systems. Teachers could also discuss measurement error for this module. Students may be unfamiliar with numerical integration. The module text provided description of several approaches (left-point rule, trapezoidal rule, Simpson's rule) and the provided spreadsheet performs these calculations based on the student-generated data.

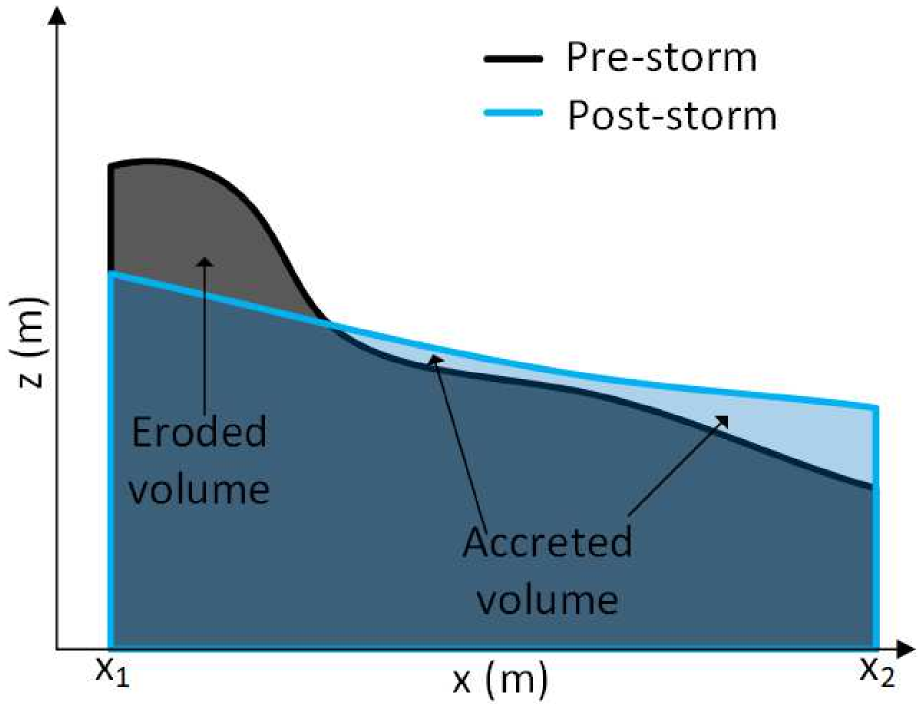


Figure 7. Simplified schematic showing the areas under the curve determined through integration and eroded and accreted volumes from pre- and post-storm measurements.

Students were asked to run the waves for 5 minutes with a low paddle frequency creating "summer" conditions. Students carefully traced the beach profile using colored pin-striping tape or grease pencil on the flume wall (blue curve in Figure 3). Waves were then run for an additional 5 minutes with a higher paddle frequency creating "winter" conditions. Students were asked their perception of the time it takes for the beach to respond to the "winter" vs. "summer" waves and explain what might be responsible for the difference. The "winter" beach profile was then traced using a different color pin striping tape or grease pencil (red curve in Figure 3). A local coordinate system was identified with cross-shore distance of $x = 0$ inches at the landward edge of the flume. Measurements can be made in US Customary or SI units. Elevation measurements to the "summer" and "winter" profile were made using a ruler with a cross-shore spacing of 2 inches and recorded into the provided spreadsheet. The spreadsheet automatically plots the two beach profiles and estimate the net volumetric change using several different estimates for integrating across the profile. Students were asked the following questions:

1. Do you expect there to be a net volumetric change in the beads that constitute the beach profile? Why might the net result be non-zero?
2. Did the beach change match your expectations?
3. What was the effect on the landward portion of the beach profile?

Students returned to the wave flume and generated a tsunami using the approach described in "Module 7: Tsunami". They were asked what they think will happen to the profile relative to the "winter" condition. The post-tsunami beach profile was traced and the procedure for beach profile measurements was completed with the spreadsheet providing the change relative to the "winter" profile.

3.3. Description of "Module 11: Application—beach nourishment"

It is estimated that 24% of sandy beaches worldwide are eroding (Luijendijk et al., 2018). Beaches provide a protective buffer from extreme events and also provide recreation opportunities that attract tourists and support many local economies. Thus, it might be important to mitigate erosion because the financial and protective benefits tend to far exceed the cost. There are a variety of methods used to protect coastlines in an effort to minimize erosion with the two most common being: 1) hard structures such as jetties, groins, or sea walls (an exercise is provided in "Module 13: Application—protecting the beach"); and 2) beach nourishment (described in this module). The latter is a common approach and is sometimes referred to as the "soft" solution.

Beach nourishment is the process whereby sand from a borrow source, usually far offshore, is dredged and delivered to the coast via barge or vessel. The sand is pumped onto the beach and moved into position with heavy machinery. The initial beach shape, called the template, may be steeper than what is expected for that particular shoreline so that natural processes can redistribute the sand. Figure 8 shows pre- and post-nourishment images from Rehoboth Beach, Delaware. The dredge delivering sand to the beach can be seen in the upper image. Tide levels are roughly the same in both images. The outflow pipes (structures oriented perpendicular to the shoreline) and the steps down to the beach from the boardwalk provide excellent perspective with regard to the nourished beach where the pipes are covered, and the steps are no longer needed as a dune was built up against the boardwalk.

The most basic tenet of beach nourishment is to increase the dry beach width adding a protective buffer and recreation area. The theory to identify the required volume uses the concept of equilibrium beach profiles (Dean, 2002), which is described in “Module 8: Beach profiles and basic theory” for the original and nourished beach profiles. The volume (V, per meter length of beach) of required sand for a particular desired additional dry beach width Δx is:

$$V = (h_* + B) * \Delta x, \qquad (4)$$

where h_* is the closure depth; location where the beach profile is expected to change little, and B is the berm height (refer to Figure 9). The total volume is then obtained by multiplying equation (4) by the project length. In a natural setting, the length may be on the order of kilometers. In the Making Waves in the Classroom exercises, the project length is the internal flume width.

The original beach profile is assumed to have an equilibrium profile shape (from Module 8). The nourished profile is shifted upward and seaward, maintaining the same equilibrium profile shape if the diameter of the nourishment sediment is the same as the original. This holds true in the

Making Waves in the Classroom exercises and students were given additional acetal beads to implement their beach nourishment plans. The closure depth, as described previously, is the depth where there is expected to be little change in elevation over time. This depth is limited in the wave flume due to the flume dimensions.

Figure 8. Pre- and post-nourishment images at Rehoboth Beach, DE.

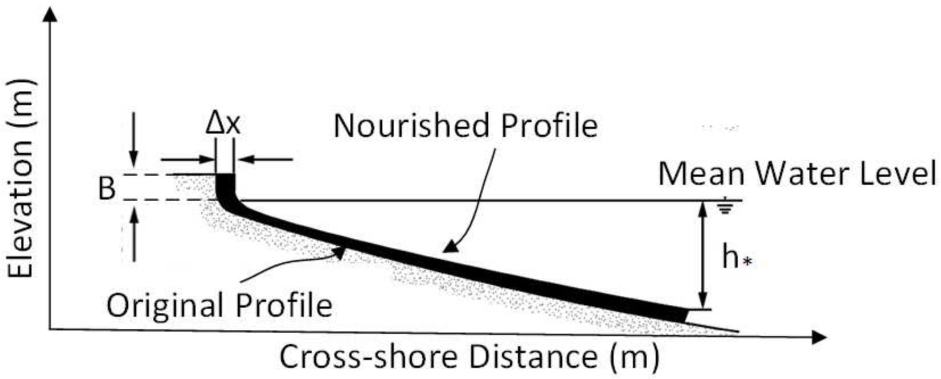


Figure 9. Schematic showing the original equilibrium beach profile and the nourished beach profile providing the additional dry beach width, Δx (Dean & Dalrymple, 2001).

Students designed a beach "nourishment" plan for the flume and then observed/quantified how their nourishment responded to the wave forcing after putting the additional beads in the flume. This module is an example where inquiry-based learning allowed the students to receive immediate feedback on their choices through direct observation of the phenomena. For example, students were not told how much additional dry beach width was needed/required, where on the profile to place the additional beads, or how to place or spread out the beads: deposited in one location or even to split the volume and place in different locations. The students discussed with their group members and developed hypotheses on the best location for placement and then tested their choice. Additionally, prior to performing the experiment the student groups presented their hypotheses to the class and defended why they made the choices they did. Afterwards, the groups explained any difference in response and quantified that difference using the beach profiling procedures described earlier. This module used SI units to facilitate familiarity in different unit systems.

Students were asked to run the waves for 5 minutes with a slow paddle speed, creating "summer" conditions. Pin-striping tape or grease pencil was used to trace the beach profile. The berm height in meters was estimated using Figure 9 as a guide. The closure depth was estimated using profile measurements but is likely to be near the distance from the still water level to the bottom of the flume. Students selected an additional dry beach width with suggested values between 0.05 and 0.1 m. The required volume was calculated using equation 4 and the measured internal flume width. The volume of beads was measured using beakers or graduated cylinders. Mass can be estimated instead using the provided bead density of 1420 kg/m^3 and the required volume in cubic meters. Students needed to consider the voids between the particles (roughly 30%) when making this calculation. Mass can be converted to weight using gravitational acceleration and then determined using a laboratory scale. Beads were then placed in the arrangement determined by the student team and waves (using the same paddle frequency) were run for 5 minutes. Students were asked to describe what they observed happening. After waves ceased, students traced and measured the profile as described earlier and entered the data into the provided spreadsheet for identifying change of beach shape and volumetric differences. Students were asked:

1) What is the final dry beach width gained?
2) Does it match the desired width?
3) Why might there be a difference between the desired and actual dry beach width gained?

If time was available, the nourished volume was removed from the flume, “summer” waves run for 5 minutes, and the experiment performed again but this time placing the nourishment beads in a different configuration. Students hypothesized how the new placement may have altered the final beach profile.

4. Assessment and Discussion

As shown in Figure 1, portable wave flumes were distributed to 14 different locations along the East Coast of the US; 13 of these locations are high schools. The accompanying wave flume modules (as described in section 3) include pre- and post-module questionnaires and worksheets. Student responses from all high school locations were aggregated to assess effectiveness of the Making Waves in a Classroom program in facilitating student learning. This section presents a subset of these data. Additionally, at the end of the program, student as well as teacher participants were surveyed for feedback on various aspects of the program. The results of the program assessment surveys are also presented in this section.

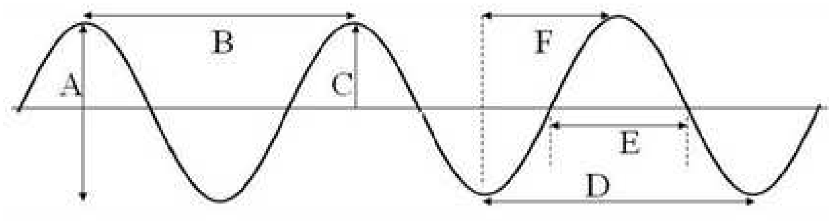
4.1. Pre- and Post-Module Questionnaires

Module 2: Wave parameters are based on fundamental concepts of a wave train. Students were given a pre-module questionnaire to gauge their baseline knowledge of the topic (Figure 10). These same questions (in addition to many others) were provided again in a module experiment and worksheet (not shown) undertaken after the teacher delivered the module lesson plan.

Pre-Module 2 Questionnaire

1) From the picture below, which letter represents the wave amplitude?

2) From the picture below, which letter(s) represents the wavelength?



3) What is a wave?

4) What is wave period?

5) How are wave period and frequency related?

6) Bobby sneezes frequently when around cats. One time he sneezed with a frequency of 0.2 Hz. How many times did he sneeze in 10 seconds?

7) Storm waves have a period of 6 seconds. How many waves will pass by a fixed boat in a minute?

Figure 10. Pre-module questionnaire for Module 2: Wave parameters.

Questions 1 and 2 in the questionnaire are multiple choice questions related to choosing a wave feature from a schematic. Student responses for these questions from the pre- and post-module questionnaires are shown in Figures 11 and 12. Pre-module, 40% of the students correctly identified the wave amplitude in question 1 by selecting option “C” (147 pre-module responses) as compared with 75% after taking the module (162 post-module responses). The most common incorrect answer for question 1 was option “A” (wave height instead of amplitude); 38% of students chose this option pre-module vs. 22% post-module. The majority of students correctly identified wavelength (options “B” or “D”) for question 2 in both the pre- and post-module questionnaires (78% vs. 91%).

Pre- and post-module questionnaire responses for the questions “What is a wave?” (Question 3 in Figure 10) and “What is a wave period?” (Question 4 in Figure 10) were also analyzed. Students provided short answers to these questions prior to receiving module information and delivery from the teacher and again following the module. Short answer data were then coded by the authors into six categories; example responses within each category are provided in Table 2. Pre-module responses for “What is a wave?” (Figure 13) largely focused on motion in the ocean or general fluid liquid flow (70% of 93 responses). The responses indicate that students largely associated waves as referring to the ocean or related to general flow. It was encouraging that students were at least able to relate waves to a medium where waves are observed. The responses changed markedly following the module delivery (Figure 13) to indicate a wave more correctly as a type or transfer of energy (66% of 158 responses).

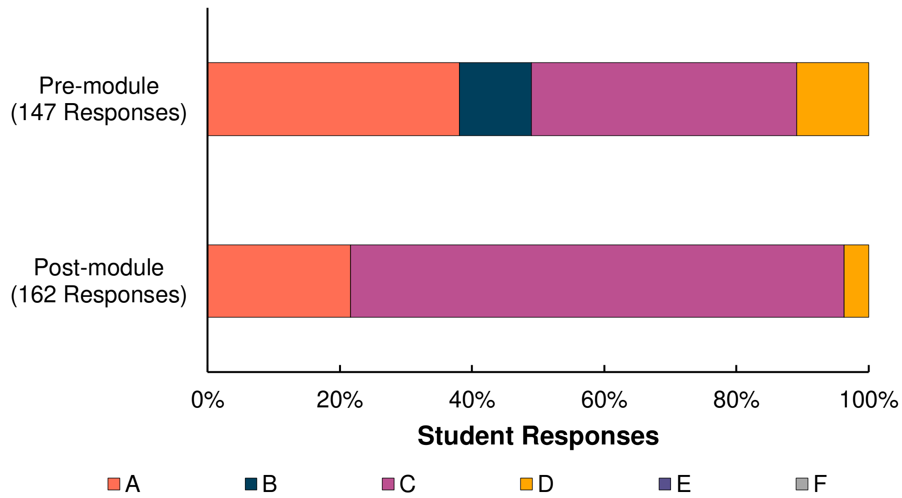


Figure 11. Student responses in pre- and post-module questionnaires where they were asked to select the option representing wave amplitude from a schematic (correct answer is “C”).

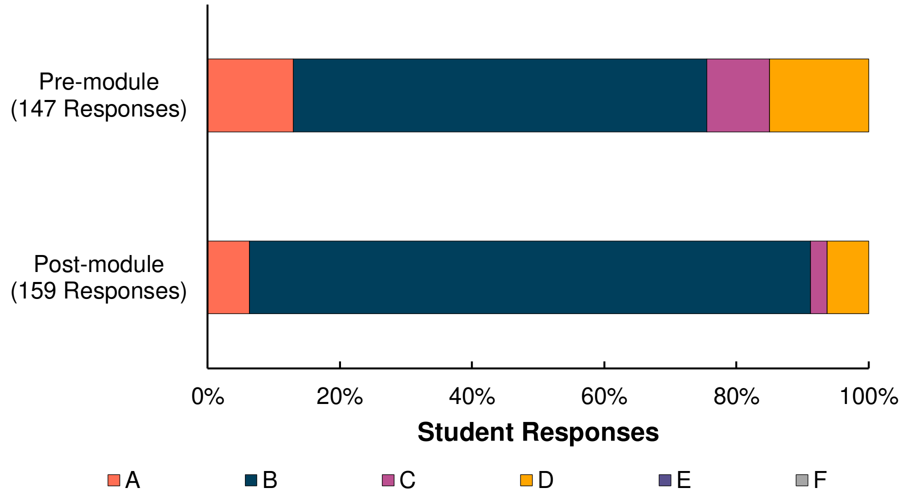


Figure 12. Student responses in pre- and post-module questionnaire where they were asked to select the option representing wavelength from a schematic (correct answers are "B" or "D").

Pre-module responses for "What is a wave period?" (Figure 14) were most related to how long a wave lasts and the time between corresponding points on a wave (70% of 105 responses). Even pre-module, many students were familiar enough with a waveform to correctly identify the period as the time between corresponding points on a wave (26% of 105 responses). The percent of students that answered the question correctly post-module (Figure 14) increased to 60% (total 148 responses). However, some students still incorrectly referred to the wave period as how long a wave lasts or distance between points on a wave, reflecting that they have not learned that these concepts are unrelated to the wave period.

Table 2. Examples of Coded Student Responses on Pre- and Post-Module Questionnaires

What is a wave?	**Example Student Responses**	**What is a wave period?**	**Example Student Responses**
Motion in the ocean	"long body of water curling into arched form" "Moving water in the ocean"	How long a wave lasts	"Time period in which waves appear" "time it takes for the wave to get to shore"
General fluid / liquid flow	"Dispersion of water" "Flow of fluid"	Distance between points on a wave	"the distance between one wave and the next" "distance between two waves passing a stationary point"
Force / disturbance	"Disturbance of fields" "A disturbance that travels through some kind of medium"	Time between corresponding points on a wave	"Time between two peaks of a wave" "time it takes to complete one cycle"
Type / transfer of energy	"Movement of energy through a medium" "Flow of energy"	Time between non-corresponding points on a wave	"amount of time between wave high and low point" "How long it takes for a wave to get form trough to crest"
Periodicity	"something that oscillates up and down" "frequency moving through matter"	Mentioned frequency	"the frequency" "how many waves you see in a period of time"
Other	"they are everywhere in nature"	Other	"Group of waves"

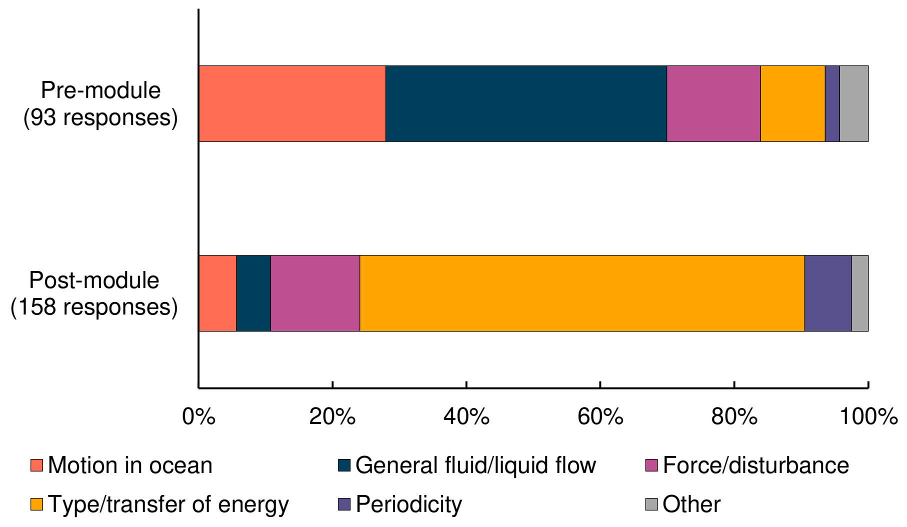


Figure 13. Student responses in pre- and post-module questionnaire for the question, "what is a wave?".

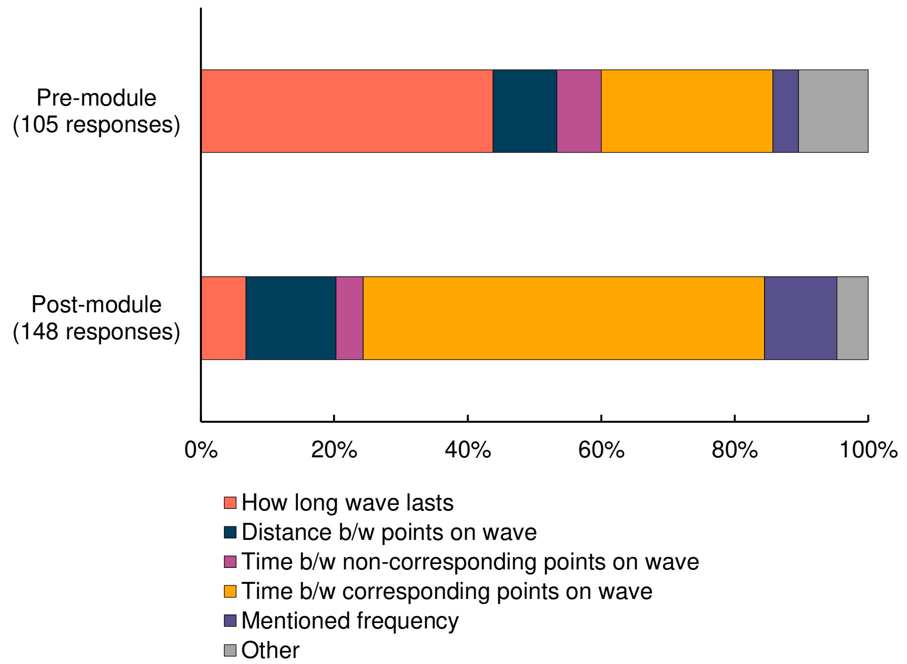


Figure 14. Student responses in pre- and post-module questionnaire for the question, "what is a wave period?".

4.2. Student Assessment of the Program

Students were surveyed using a range of questions related to program influence, pre- and post-learning achievements and perception about the modules and apparatus (questionnaire shown in Table 3). There were 89 responses to this student survey, the respondents were from grades 10 (3% of respondents), 11 (46% of respondents) and 12 (51% of respondents). The majority of the student respondents indicated that they found the modules not too hard or too easy (62%).

Sixty-eight percent of the respondents indicated that the program increased their interest in studying science/engineering and 88% of the respondents indicated that the program increased their understanding of science/engineering (Figure 15). Students were asked to judge the amount of learning before and after the program (Figure 16); 97% of the students responded either "I know a lot" or "I know a moderate amount of material" after the program as compared with 33% before the program, indicating that students perceived a substantial increase in their understanding of basic principles of wave and sediment transport processes due to the program.

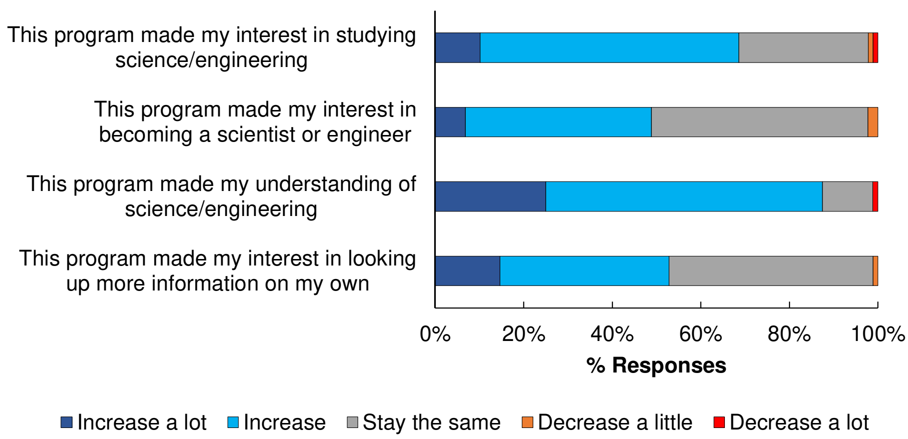


Figure 15. Responses to questions related to program influence in the student program assessment survey.

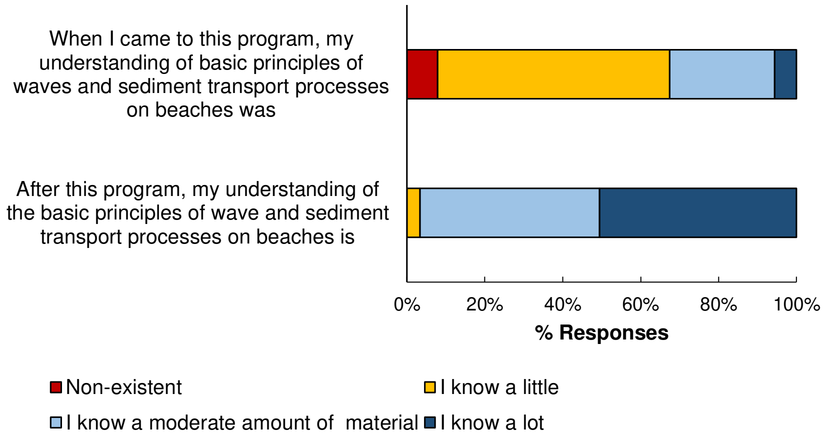


Figure 16. Responses to questions asking students to judge their learning before and after the program in the student program assessment survey.

Table 3. Questionnaire distributed for student assessment of the program.

Question Type and Wording	**Response Type**
Demographics: What grade are you in?	Multiple choice (grades 9-12)
Perceived Ease/Difficulty: The program I participated in was	5-scale Likert response: Very hard, Somewhat hard, Not too hard or too easy, Somewhat easy, Easy
Program influence: This program made my: • interest in studying science/engineering • interest in becoming a scientist or engineer • understanding of science/engineering • interest in looking up more information on my own	5-scale Likert response: Decrease a lot Decrease a little Stay the same Increase Increase a lot
Learning: • When I came to this program, my understanding of basic principles of waves and sediment transport processes on beaches was • After this program, my understanding of the basic principles of wave and sediment transport processes on beaches is	Multiple-choice Non-existent I know a little I know a moderate amount of material I know a lot
Overall program perceptions: • The wave flume module instructions were understandable • The wave flume modules helped me to understand wave and beach process concepts from class • The wave flume modules did NOT allow me to work in a group setting where all participated I thought the wave modules were fun and worthwhile	5-scale Likert response: Strongly disagree Disagree Neutral Agree Strongly agree
Perceptions of specific parts: • Sensor data in the wave flume modules was helpful to my understanding • The Excel spreadsheets were useful to help me visualize and think about the data on the data logger • I like to manipulate the forcing conditions and/or beach shape and/or protection mechanisms to assist in learning coastal processes concepts • The use of plastic pellets as a sand surrogate was beneficial to observe response quickly when forcing conditions were altered	5-scale Likert response: Strongly disagree Disagree Neutral Agree Strongly agree
Qualitative Comments: What are the best attributes in the wave flume modules and wave flume apparatus? What can be improved with the wave flume modules and apparatus?	Text

Responses to questions assessing student perceptions about specific parts of the program as well as the overall program were positive (Figures 17 and 18). The majority of the student respondents perceived the wave flume module as worthwhile and entertaining, and as a vehicle to understand coastal processes. Students were content with the apparatus, ability to change forcing conditions and provided sensors and spreadsheets for analysis (Figure 18). In their responses to the open-ended questions in the program assessment, students named the ability to manipulate the wave flume apparatus and visual demonstration of wave formation and action as the best attributes of the module. Some comments noted that water splashed out of the tank at certain paddle speeds.

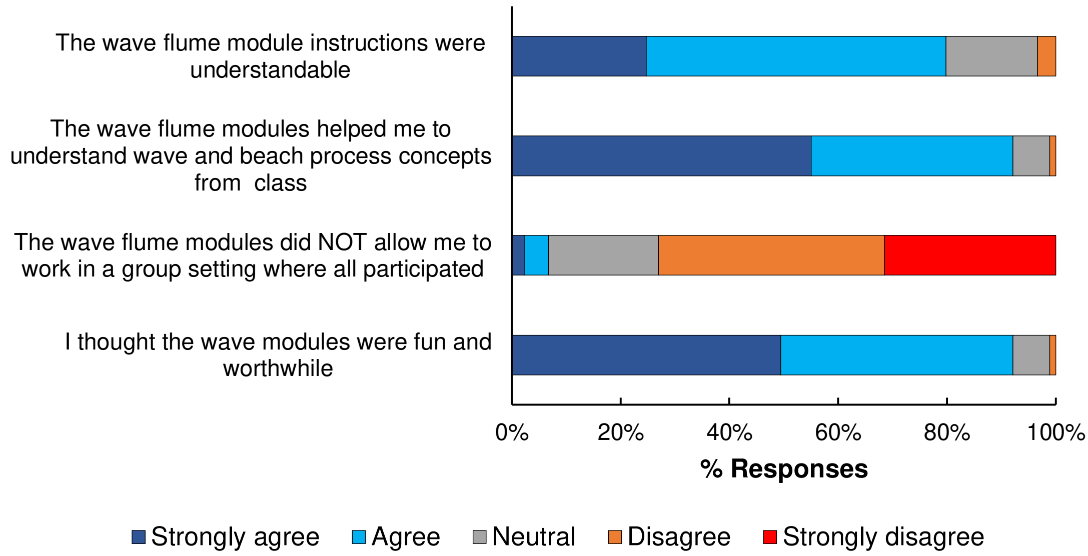


Figure 17. Student perceptions of overall program from student program assessment survey.

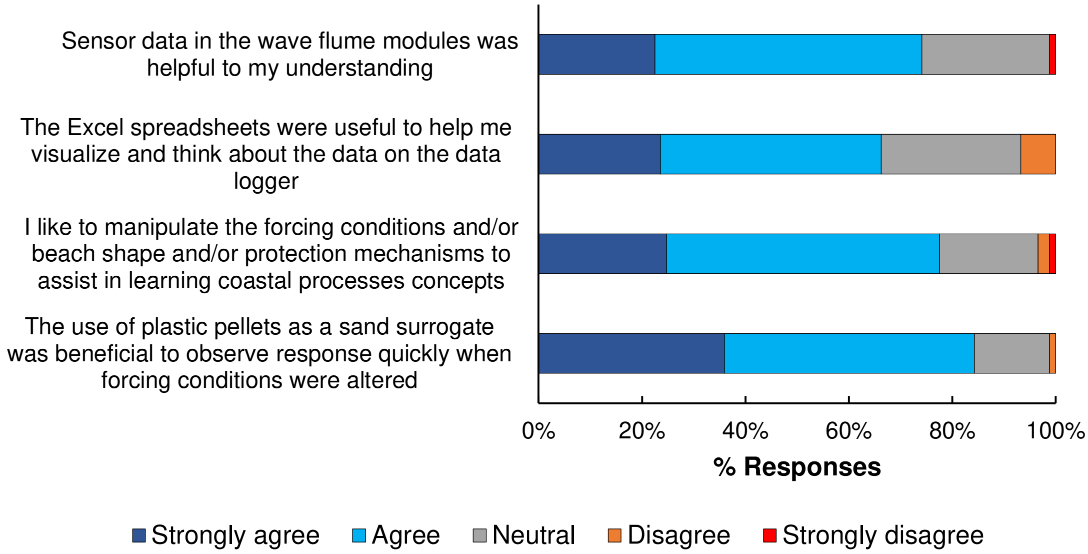


Figure 18. Student perceptions about specific program parts including sensor data, Excel spreadsheets, plastic pellets, and apparatus settings from student program assessment survey.

4.3. Teacher Assessment of the Program

At the end of the program, teachers who implemented the portable wave flumes in their classrooms were surveyed to determine their satisfaction with the program (questionnaire shown in Table 4). Twelve out of the 13 teacher participants filled out this program assessment survey.

Based on responses to questions related to perceptions of student learning, 9 out of 12 teachers agreed or somewhat agreed that students generally had a rudimentary understanding of coastal processes prior to the program, but all 12 teacher respondents agreed that student understanding was enhanced following the program. Figure 19 shows responses from the teacher program assessment survey on both positively and negatively worded questions on module efficacy. In general, the teachers agreed that the modules are useful in teaching coastal processes with enough flexibility.

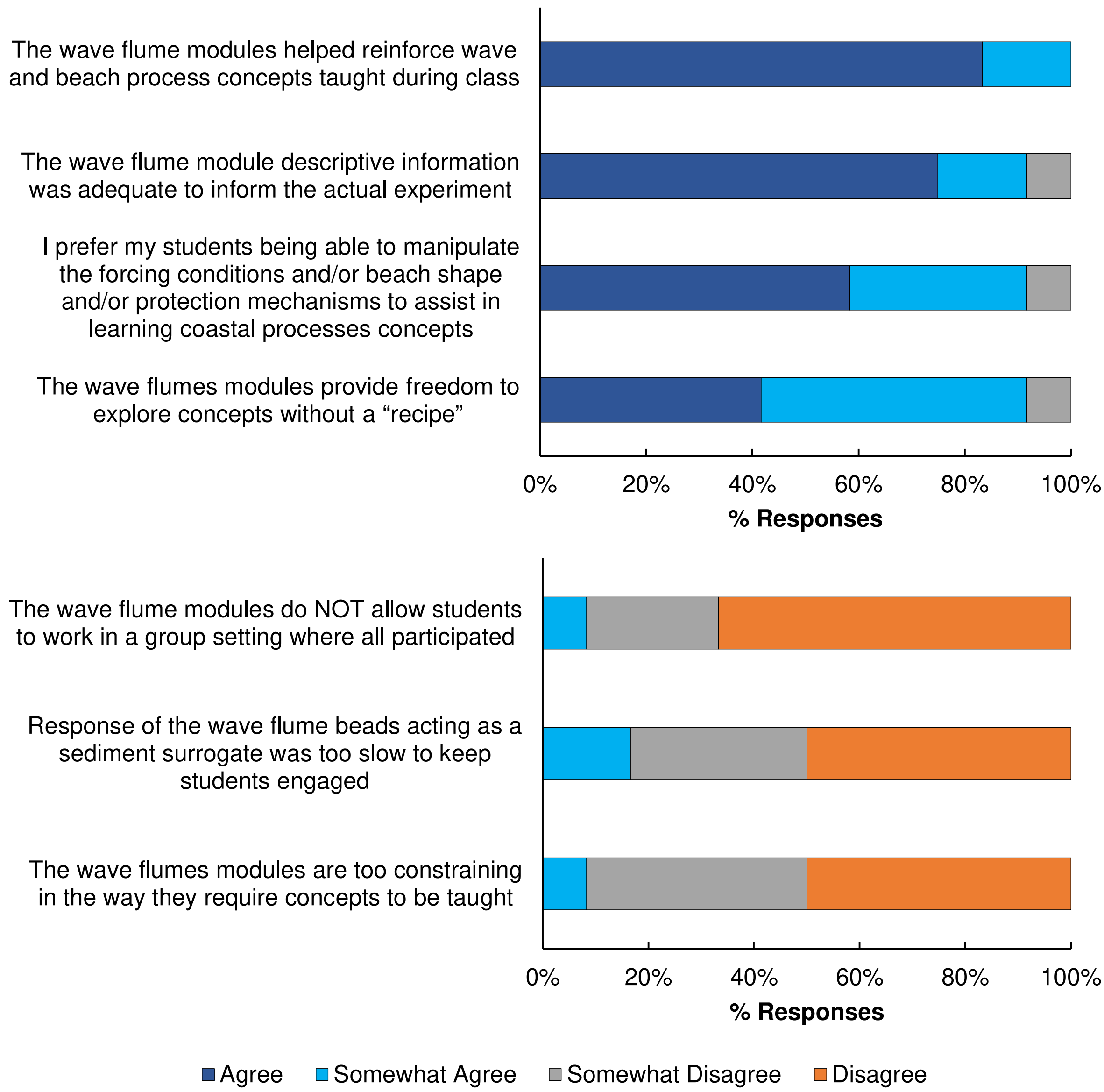


Figure 19. Responses to questions related to module efficacy from teacher program assessment survey.

Table 4. Questionnaire distributed for teacher assessment of the program.

<table>
<tr><th>Question Type and Wording</th><th>Response Type</th></tr>
<tr><td>Perceptions on student learning:
Prior to exposure to the wave flume and modules, my students had a rudimentary understanding of the basic principles of wave and sediment transport processes on beaches.
Following exposure to the wave flume modules, my students understand and can describe the basic principles of wave and sediment transport processes on beaches.
The modules and flume apparatus contributed to my students' better understanding of coastal engineering and coastal processes.</td><td>5-scale Likert response:
Strongly disagree
Disagree
Neutral
Agree
Strongly agree</td></tr>
<tr><td>Positively worded questions on module efficacy:
The wave flumes modules provide freedom to explore concepts without a "recipe".
I prefer my students being able to manipulate the forcing conditions and/or beach shape and/or protection mechanisms to assist in learning coastal processes concepts.
The wave flume module descriptive information was adequate to inform the actual experiment.
The wave flume modules helped reinforce wave and beach process concepts taught during class.</td><td>5-scale Likert response, same as above</td></tr>
<tr><td>Negatively worded questions on module efficacy:
The wave flumes modules are too constraining in the way they require concepts to be taught
Response of the wave flume beads acting as a sediment surrogate was too slow to keep students engaged.
The wave flume modules do NOT allow students to work in a group setting where all participated.</td><td>5-scale Likert response, same as above</td></tr>
<tr><td>Usefulness of specific program parts:
Wave flume modules
Wave flume module solutions and "How to"
Acoustic sensor data
Impellor sensor data
Provided Excel spreadsheets
Structural elements (seawall, stones)</td><td>4-scale Likert response:
Very useful
Useful
Somewhat useful
Not useful</td></tr>
<tr><td>Future use:
Next time I plan to use the flume:
Not at all, With some changes, or Same as I did this time</td><td>Multiple-choice</td></tr>
<tr><td>Qualitative comments:
What are the most positive aspects of the wave flume modules and apparatus?
What are the most negative aspects of the wave flume modules and apparatus?</td><td>Text</td></tr>
</table>

• What new or improved modules or apparatus modifications would you like to see/have in the future?	

Teacher responses to questions related to the usefulness of the different parts of the wave flume were mostly positive (Figure 20). However, teachers did not find all implements completely useful. The sensor usefulness received the lowest scores relative to others (Figure 20). The initial goal was to use inexpensive sensors that may not have performed well upon implementation. The acoustic sensor was used to track the free surface and generally performs well. Issues arise when steep sloping features (wave fronts) pass under the sensor. The acoustic beam spreads out from the sensor as a cone that struggles to capture the correct distance due to the gradient in water level in the cross-shore direction. An option would be to use a higher resolution acoustic sensor or a sensor with a different frequency and narrower acoustic cone. There would be a commensurate increase in cost. A second option is to use a pressure transducer. A pressure transducer was indeed tested for the program. However, the small wave amplitudes generated in the wave flume made it difficult to resolve the waves. In addition, a custom pressure transducer was needed for the small pressures that were attempted to be resolved. A third option would be to use a red laser for distance. Cost and safety issues were a concern. Thus, the acoustic sensor was chosen for feasibility and general data collection capability away from the wave front. The impeller current meter was also seen as a weak point of the apparatus and system delivery. The issues with the impeller are noted having a minimum velocity threshold for motion, hysteresis upon motion initiation, and the inability to determine flow direction. It is not believed a cost-effective miniature current meter exists for high school education that would resolve direction reversing flows in the wave flume. A current meter will not be included in future systems.

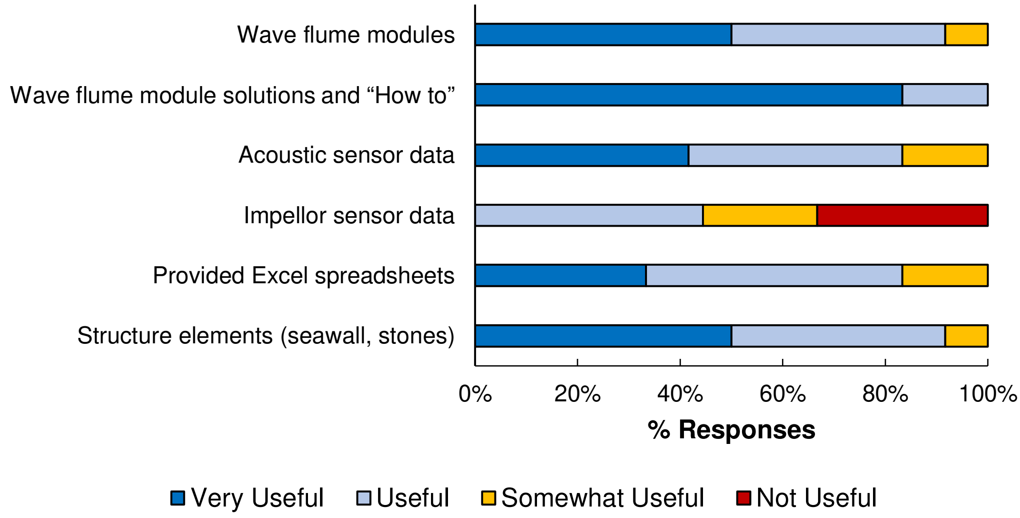


Figure 20. Perceptions about usefulness of different elements of the wave flume modules from teacher program assessment survey.

All teacher respondents indicated that they would use the portable wave flumes again; 10 out of 12 responses indicated that they would make a few changes. Comments on planned changes mainly focused on organizational and pedagogical changes to enhance integration into the curriculum and allowing more time for student group work. Qualitative comments from the teacher respondents indicated that the most positive aspects of the wave flume modules and apparatus are improved student engagement through visual demonstration of coastal processes and the hands-on activities that the modules facilitate.

5. Conclusions

The Making Waves in the Classroom Project has provided 14 wave flume apparatuses and accompanying modules to 13 high schools on the east coast of the United States (and one museum). Students use the apparatus for inquiry-based, hands-on learning of coastal engineering and coastal physical processes. The modules provide introductory information for teachers and students and guidance on module usage. However, modules were designed purposely to engage students in testing different scenarios and describing observations through qualitative observations and quantitative analysis (using measurements and sensor data). Pre- and post-module worksheets and overall program surveys were used as assessment instruments to gauge effectiveness of the program. The student and teacher assessment results indicate that the portable wave flumes and associated modules were successful in helping students understand coastal processes in an engaging and hands-on manner. All teachers surveyed indicated that they plan to use the flume again. The acoustic sensor had some utility for the modules and will be used in future iterations of the program. The current meter was identified as a weak aspect of the program and will not be incorporated in the program moving forward.

Wave flume plans, modules, and module solutions (for teachers) are freely available via the corresponding author's webpage, http://sites.udel.edu/jpuleo (Puleo, 2019) or by contacting directly the corresponding author. Our hope is to expand usage by other teachers/agencies leading to increased STEM literacy/interest in high school students.

Acknowledgments

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