User's Guide to the Temperature Sensor Method for Determining Tidal Inundation Regime

This User's Guide is part of a larger report, which is available at http://www.ciceet.unh.edu.

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Introduction

The temperature sensor method (hereafter, the "Method") is a method for determining tidal inundation frequency and duration in intertidal wetlands. The Method provides a low-cost

alternative to traditional water-level loggers and elevation surveys. In estuarine wetlands of Oregon, USA, we have successfully used the Method to detect tidal inundation events in all seasons and in a variety of wetland habitat classes using several deployment methods. This user's guide describes the equipment needed, deployment methods, and how to interpret the results.

Please note that this guide describes the use of the Method in outer coast estuaries of Oregon. Results and interpretation may vary in different regions and landscape settings.

How the temperature sensor method works

The Method relies on the difference between air and water temperature to detect tidal inundation. Basically, the temperature at a particular "variable" logger is compared to reference water and air temperatures (obtained with other loggers). In our region, tidal inundation at a variable logger was marked by rapid convergence between the "variable" logger's temperature and the reference water temperature, and divergence between the "variable" logger's temperature and the reference air temperature. We refer to this pattern as the "inundation signal." Conversely, time of re-exposure of the "variable" logger was marked by divergence between its temperature and the reference water temperature, and convergence between the "variable" logger's temperature and the reference air temperature (the "re-exposure signal").

Equipment needed

Temperature loggers

There are a variety of temperature loggers available, at a range of prices and functions. Two examples are shown below. We used iButtons, because of their low price and small size (which made them very easy to deploy). In this Guide, we use the words "iButton" and "logger" interchangeably.

Examples of Low-Cost Temperature Loggers Available:
1. Maxim iButton temperature logger (part # DS1921G) (Figure 1)
   - Website: http://www.maxim-ic.com/datasheet/index.mvp/id/4023
   - Unit price: $14-25/logger (discounts with bulk purchase)
   - Size: Approx. 1.6cm diameter, 0.6cm thick
   - Memory: 2,048 measurements
     (higher capacity models available at higher cost)
   - Accuracy: 1°C
   - Resolution: 0.5°C

Figure 1. iButtons

2. Onset pendant loggers (5 models available) (Figure 2)
   - Website: http://www.onsetcomp.com/products/data-loggers/ua-001-08
   - Unit price: $36-42/logger (discounts with bulk purchase)
   - Size: 5.8 x 3.3 x 2.3cm
   - Memory: 6,500 measurements
     (higher capacity models available at higher cost)
   - Accuracy: 0.47°C at 25°C
   - Resolution: 0.1°C at 25°C

Figure 2. Onset pendant logger (not to scale)

Waterproofing the loggers

For this Method, the loggers must be waterproof. iButtons are water-resistant, but not waterproof. We tested three waterproofing techniques: knotting the iButtons inside small rubber balloons, sealing their seams with silicone sealant, and sealing them inside plastic bags using a household vacuum sealer. We found that the balloons leaked, and the silicone sealant tended to flake off in the field. The vacuum sealer worked very effectively and consistently, and was very durable in the field. Vacuum sealer bags were cut to size from rolls of vacuum sealer bag material; the bags were made just larger than the iButtons (allowing for adequate edge to apply the vacuum). The vacuum sealer creates close contact between iButton and the surrounding water, maximizing the speed of transmission of water temperature to the logger. Initially, we were concerned that the application of a vacuum might affect iButton function, but our tests showed no evidence of any effects on the loggers. However, we recommend testing this in your own studies and if application of a vacuum seems undesirable, the sealing function of the vacuum sealer could used without the vacuum.

If the temperature logger is directly exposed to saline water, the logger should be made of a material that won't corrode under those conditions. Because we sealed the iButtons in vacuum sealer bags, we did not test their corrodibility.

Hardware to connect to the computer

iButtons are launched and downloaded by connecting them to a computer. To do this, you will need a probe and most likely an adapter. Details are provided at the manufacturer's website, http://pdfserv.maxim-ic.com/en/an/AN4373.pdf. We used a "blue dot" probe (part # DS1402D-DR8+) USB adapter (part number DS9490R#). We recommend checking with the manufacturer for the specific parts you need.

Housings for field deployment

For best results, the iButtons should be protected from direct sun to reduce temperature changes caused by solar warming. White PVC pipe can be used to construct housings by cutting to an appropriate length, drilling for ventilation, and capping to shade the iButtons fastened inside. For further details, see "**How to deploy the loggers**" below.

Software

Interface software is needed to launch the iButtons, download the data, and interpret the results. There are several requirements for interface software for the Method:

1. The software should automatically synchronize iButtons with the computer's clock;
2. It should enable delayed, simultaneous launching of several iButtons at a specific time in the future, such as "2:00 p.m. on December 1, 2012."
3. Since data interpretation relies on visualizing temperature curves in a graph (e.g., Figures 8 and 10), the software should be able to display the temperature curves of several iButtons on the same chart. Alternatively – and for even more flexibility -- it may allow export of the temperature data to a spreadsheet or graphics program such as Microsoft Excel, where the results can be viewed graphically.

Free interface software to launch and download iButtons is available via a search engine at the manufacturer's website (http://www.maxim-ic.com/products/ibutton/example/), but neither the search engine nor the software is user-friendly. We found that third-party software for iButtons was easier to use and had better features than the manufacturer's software for the temperature sensor method. Many third-party software options for use with iButtons are listed at the manufacturer's website (URL below):

(http://www.maxim-ic.com/products/ibutton/solutions/search.cfm?Action=DD&id=253). We tested several, and found that eTemperature from OnSolution worked best for us. Contact the manufacturer at sales@onsolution.com.au for current availability and pricing. If you use another type of temperature logger, the manufacturer's software may prove adequate for this Method.

Additional equipment for data validation

Data validation is described in "**How to validate your results**" below. Equipment needed includes:

1. **Water Level Loggers:** These instruments generally measure pressure and include software which converts the pressure data into water depth values. Water level loggers can be used to validate temperature logger data by comparing the time when the water reached the temperature logger's elevation to the time of the "inundation signal" at that sensor (and vice versa for re-exposure). See "**How to validate results**" below. We used Onset HOBO water level loggers (model U20-001), since we have found these to be reliable, and the accompanying software is user-friendly. However, other water level loggers would be equally suitable.

2. **Elevation survey equipment** – to determine elevations of temperature loggers and water level logger. Consult with survey professionals to find out how to get accurate elevations in your study area.

How to deploy the loggers

Timing for field deployment

The strongest "signal" of tidal inundation from temperature loggers occurs at night. During the day, temperature "noise" (variability) due to solar warming of air and soil by the sun can create too much "noise" to see the signal clearly. Therefore, plan your deployments carefully so that the tides you want to monitor occur at night. For example, in a region with mixed tides (one higher high tide and one lower high tide each day), you may find it useful to detect inundation by the higher high tides. In this case, choose a deployment period when the higher high tides occur at night.

Deployment methods

We have had useful results from two different deployment methods: loggers arrayed in strategic locations on the wetland surface ("surface loggers," red dots in Figure 3); and loggers placed vertically on posts in tidal channels ("vertical post arrangement," blue dots in Figure 3). The wetland surface arrangement is useful for gathering spatially accurate information on tidal

inundation regime across an entire study area, while the vertical post arrangement is best for measuring the height or speed of inundation at a particular location.
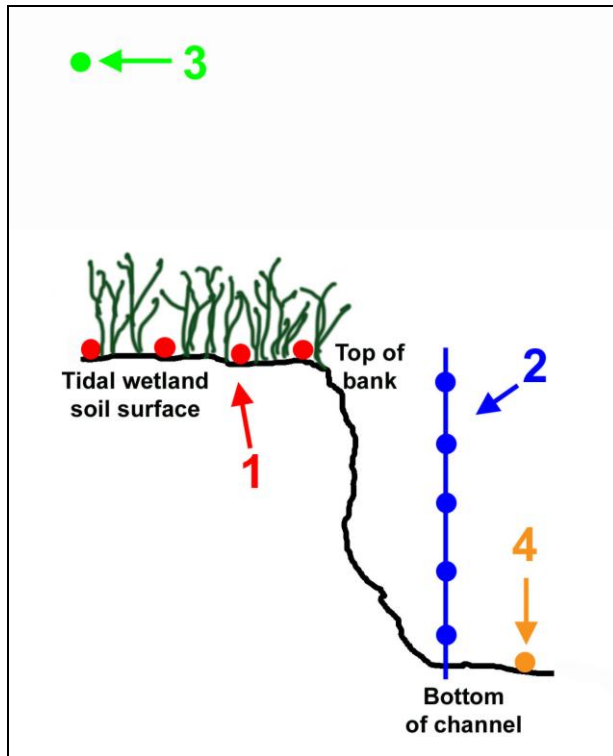

Figure 3. Temperature logger deployment methods, and reference loggers: 1) "surface loggers" placed at strategic locations on the wetland surface or channel banks (red dots); 2) "vertical post arrangement" in a tidal channel (blue dots); 3) air temperature reference logger (above highest tide, on tall post or tree – green dot); 4) water temperature reference logger (orange dot).

Housing for surface loggers

An example of a housing for a surface logger is a short PVC sleeve with the logger wired to the center of the sleeve (Figure 4). The PVC is then wired to a wooden stake which is pounded into the marsh surface. The vertical position of the logger must remain stable in wind and currents. Many other housings and installation methods would be equally effective.

Figure 4. Deploying a surface logger inside a protective PVC sleeve. PVC sleeve and temperature logger are wired to a stake which is pounded into the marsh surface. After installation, the PVC sleeve is resting directly on the surface.

Housing for vertical post arrangements

In this arrangement, iButtons are wired to a wooden dowel, which is then placed inside a heavily perforated PVC pipe (Figure 5). To reduce solar warming during daytime, the wooden dowel should remain in the center of the PVC, so the iButtons do not contact the PVC (which will be warmed by the sun). The PVC pipe is capped with a loose fitting lid (a yogurt tub works well) to shade the pipe, yet allow ventilation.

Figure 5. Deploying a vertical post arrangement in a tidal channel. The white PVC pipe contains a wooden dowel with temperature loggers attached. The pipe is wired to a metal post, which is pounded into the channel substrate.

Deploying reference temperature loggers

As described in the Introduction, the Method requires the use of reference air and water temperature data. One reference logger should be placed in a well-shaded location well above tide level to track ambient air temperature ("air temperature reference," Figures 3 and 6). A second reference logger should be placed in the lowest possible location within a tidal channel ("water temperature reference," Figures 3 and 7). Place these reference loggers near your other deployments. On a large site, you may wish to deploy several air and water reference loggers to capture variability across the site. These reference data will enable you to detect the inundation signal in data collected by marsh surface and vertical post loggers, by comparing the temperature curves.

Figure 6. Air temperature reference logger wired to a shrub well above tide level, in an Oregon scrub-shrub tidal wetland.

Figure 7. Water temperature reference logger located near the bottom of a tidal channel.

Launching the loggers and synchronizing clocks

Loggers are generally launched in the office, with a delayed start time corresponding to your planned time of field deployment. You can use manufacturer or third party software to launch the temperature loggers. Launch all loggers for a particular study with the same data collection interval and the same start time. Short logging intervals (e.g. 5min) give the most precise results, but fill up the logger's memory faster. We used 12min intervals, which gave reasonable results and allowed 21 day deployments before memory was full (for iButton model DS1921G).

Loggers obtain the time stamp from your computer when launched, so be sure your computer's clock is accurate before you launch the loggers. The best way is to synchronize your computer's clock with internet time. Note whether you launched relative to daylight savings time or standard time; this is important if you validate your results using a water level logger launched on a different date(see "**Validation with water level logger data**" below).

How to graph, visualize and interpret results

Use manufacturer or third party software to download data from the temperature loggers. After downloading, display the data in graphic format to visualize the inundation signal. You may be able to graph the data in the manufacturer's software, or you may wish to use third party software (see "**Software**" above). Temperature should be graphed on the y-axis, and date and time on the x-axis. A second y-axis may be used to incorporate validation data from a water level logger.

Inundation events are signaled by abrupt directional changes in temperature (Figure 8), which we call the "inundation signal." In our studies (Oregon outer coast tidal wetlands), the signal consists of an abrupt rise in temperature towards the water reference temperature at inundation, and an abrupt cooling towards the air reference temperature when the tide recedes. These abrupt temperature changes are best detected during night-time high tides. Daytime high tides are harder to detect, due to solar warming that obscures the signal.

Temperature curves from the vertical post arrangement show sequential inundation according to temperature logger height. In Figure 8, note the sequential night-time inundations from the bottom upwards, with the lowest temperature logger (green) inundating first and the topmost logger (yellow) inundating last. Also notice the increases in air temperature during the day, emphasizing the importance of focusing analysis on the night-time tidal inundation signals. In this deployment, however, even daytime tides were easily detected due to the deep tidal channel, forested vegetation class, and minimal solar warming.

Temperatures in Channel 2
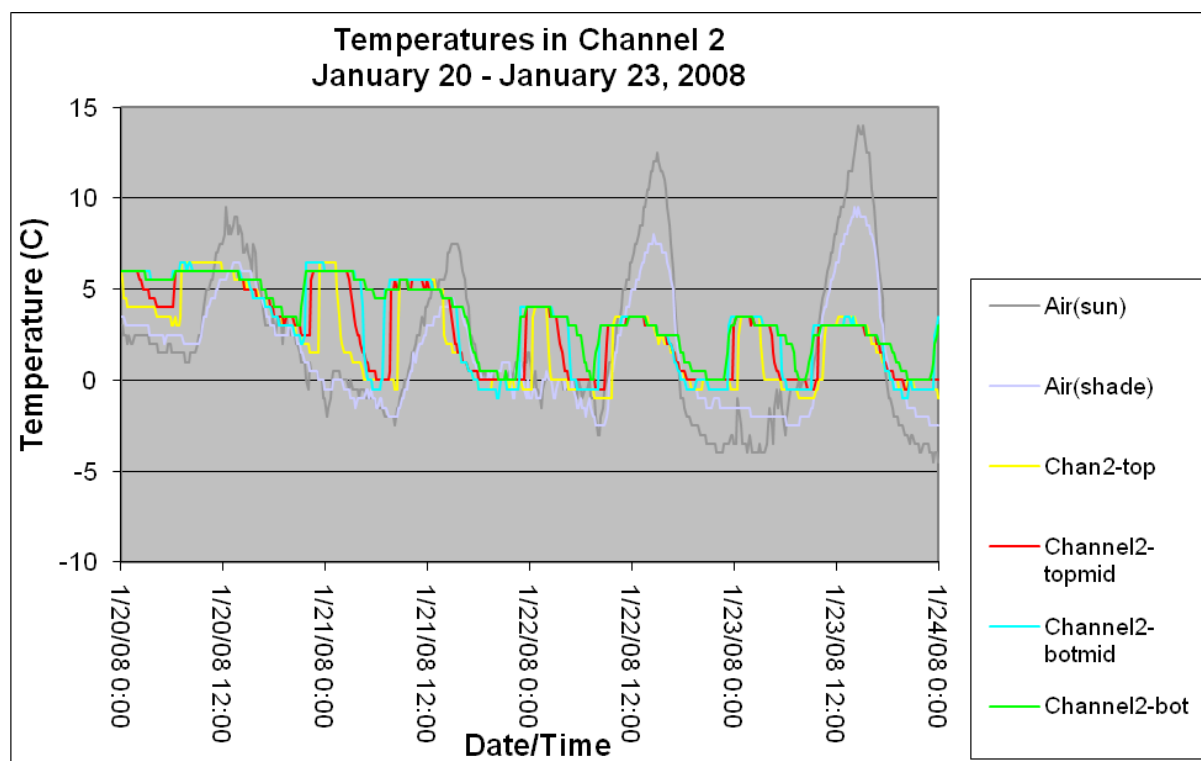**January 20 - January 23, 2008**

Figure 8. Graph of temperature logger data obtained from a vertical post deployment (colored lines); air temperature references in gray. An abrupt, vertical rise in temperature is the inundation signal for each temperature logger. Note: The bottom-most temperature logger (green), located deep in the channel, acted as the channel reference temperature logger.

How to validate results

Since the Method is new, we recommend validating the Method for your specific geographic region. Validation is the process of checking to make sure your results are accurate and your interpretation of the data is correct. In other words, validating your data will prove that the Method is working as expected, and the inundation and re-exposure "signals" that you are seeing in the temperature curves really did represent inundation and re-exposure events in the field. Validation is only needed once in a geographic area (though you might need to repeat the validation in different seasons if your climate is very seasonal). Once you have validated the Method, others can use the Method with confidence in the same area.

Your results can be validated using visual observation or a commercially available water level logger.

Using the vertical post arrangement for validation

For validation of the Method, it's easier to interpret data from a vertical post deployment. This is because the vertical post loggers inundate sequentially over a relatively short time, and if the Method is working properly, the temperature curves clearly show this sequential inundation (see **Figure 8**). However, validation can also be performed using wetland surface loggers (see the example in **Figure 10**).

Validation by visual observation

The simplest way to validate your temperature logger results is to observe the incoming tide as it inundates your deployed temperature loggers. Record the time when each iButton inundates, using an accurate timekeeping device that is automatically updated (e.g. GPS unit or cell phone). After downloading the temperature logger data, you will be able to compare your visual observations to the "inundation signal" shown by the temperature curves. Make sure your timekeeping device (watch, cell phone, etc.) is synchronized with the temperature loggers. Since the time clocks of temperature loggers generally synchronize to the clock of the computer used to launch the loggers, you should synchronize your field timekeeping device with your computer when you launch your temperature loggers.

Validation with water level logger data

For a more rigorous validation, you can use a water level logger which continuously records water levels. You can leave the temperature loggers and water level logger in place for many tide cycles, unlike visual validation, which is generally limited to a single inundation event. Validation across multiple tide cycles can help you learn to interpret different inundation signals – valuable for guiding your future work with the Method.

For water level logger validation, you need accurate elevation data for the water level logger and for each temperature logger. In the test setup illustrated in Figure 9, where the water level logger is deployed right next to a vertical post deployment of temperature loggers, you can simply measure the relative elevations of all instruments with a bubble or laser level and a tape measure. If the level logger and temperature sensors are not directly adjacent (for example, to validate results from temperature sensors arrayed across a large tidal wetland site), you will need high-accuracy elevation survey data to determine the relative elevations.

Figure 9. Side-by-side installations of a water level logger (in white PVC pipe "stilling well" at left),and vertical post deployment of several iButton temperature loggers (in vertical perforated PVC pipe at right). Deployment is located in a deep tidal channel in a forested tidal wetland in Oregon.

When you launch the water level logger and temperature loggers, set them to the same data collection interval and make sure all time clocks are synchronized (see "**Launching the loggers and synchronizing clocks**" above). To validate your results, compare the predicted time of inundation for each temperature logger to that temperature logger's "inundation signal" (Figure 10). The predicted time of inundation based on level logger data is the time at which the level logger shows a water level equal to the elevation of the temperature logger.

For accurate validation, it is very important to follow all recommended procedures to make your water level logger data as accurate as possible. For example, a water level logger that uses a pressure sensor needs to be adjusted for barometric pressure. Some water level loggers make this adjustment internally using a "vent," but others require "barometric pressure compensation" after data collection. The accuracy of your water level logger should also be checked immediately before it is used. Consult your water level logger manual for correct procedures.
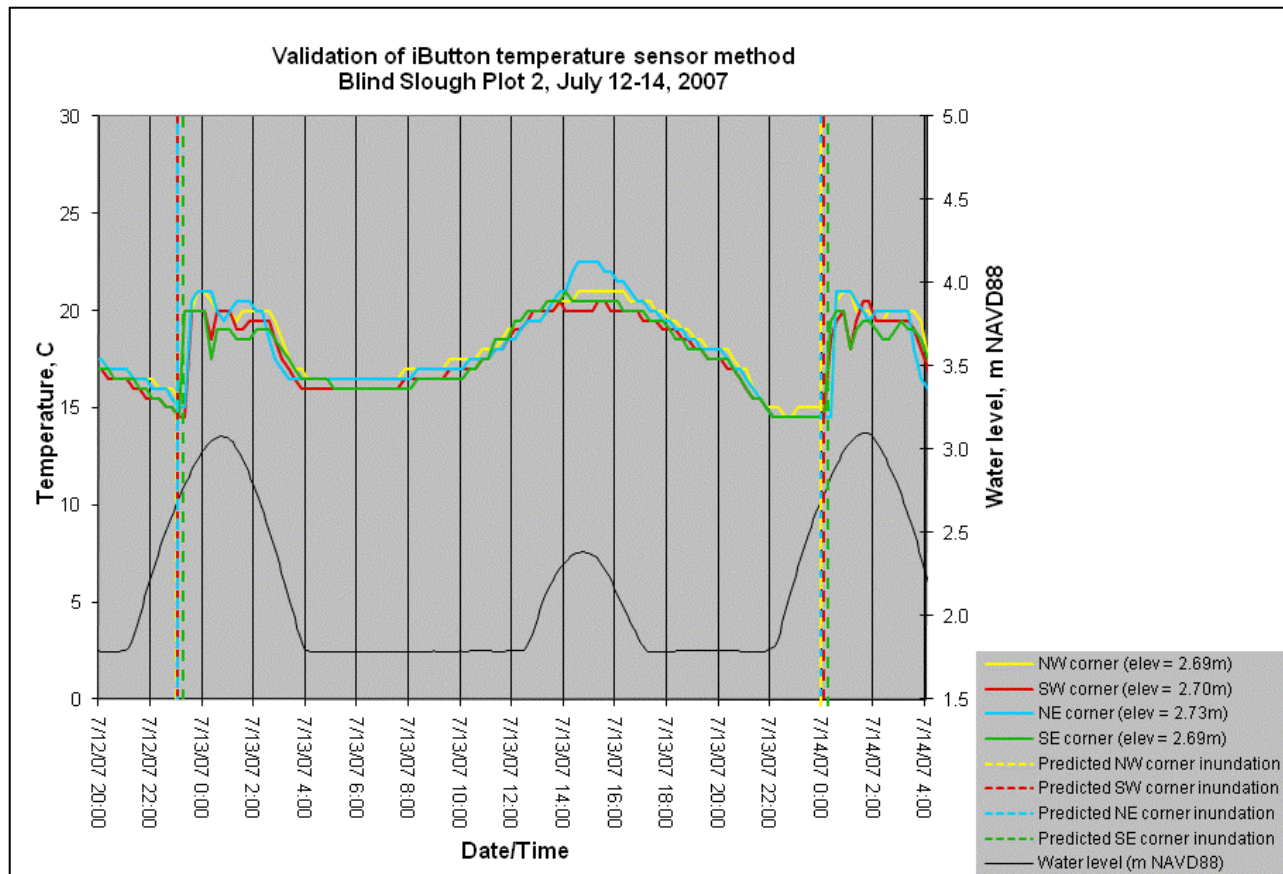
Figure 10. Validation of the temperature sensor method at a tidal swamp in the Columbia River estuary of Oregon, USA. Colored lines are the temperatures from several wetland surface loggers at varying elevations (scale on left axis). The water level from the water level logger is the black curve (scale on right axis) recorded in the channel with a water level logger. Vertical lines represent the predicted inundation time for each temperature logger (colors match the temperature curves). ***Note that only the sudden temperature changes correspond to inundation events; the broader upward temperature curve during daytime represents solar warming of the wetland surface.***

Using the Temperature Sensor Method for spatial analysis of tidal inundation

When using a water level logger to predict inundation time for distant temperature loggers, there will generally be a delay between the predicted inundation times and the actual inundation times, with a longer delay for more distant sensors. In other cases, delays between predicted and actual inundation times may be associated with dense vegetation, highly sinuous channel morphology, beaver dams, or other factors. You can use temperature sensors to study these factors and precisely determine differences in inundation regime across a large site.

Advantages and disadvantages of the method

Advantages

The Method is a low-cost and high-resolution way to measure and monitor tidal inundation regime. Compared to the traditional approach of establishing a tide gauge (water level logger) and surveying elevations to characterize tidal inundation across an entire wetland site, the Method provides inundation information at much higher temporal and spatial resolution, because

temperature sensors are placed directly on the wetland surface of interest. Because of their low cost, many temperature sensors may be deployed at a fraction of the combined cost of a single water level logger and survey equipment or survey contractor.

For an intensive site study, multiple temperature loggers can be deployed in combination with a single water level logger to precisely track differences in inundation regime across a large site. The water level logger is used to provide a predicted inundation time for each temperature logger, and delays in inundation can be visualized. These delays may correspond to distance from the water level logger, or may be due to highly sinuous channels, dense vegetation, beaver dams, or other factors. Using traditional methods, such as a single water level logger, the investigator must extrapolate inundation times from a single source. Such extrapolation may be inaccurate because water does not move instantaneously across a site.

Disadvantages

On the negative side, the data collected from temperature loggers is "binary" – it only shows whether or not the logger is inundated at a particular time. If the temperature logger did not inundate, there is no way to determine how close the water came to the logger's spatial location and elevation. By contrast, a water level logger shows the depth of water above the logger. Luckily, this disadvantage can be greatly reduced by using the vertical post deployment method, which reveals depth of inundation by comparing the sequential inundation times for each temperature logger in the vertical array.

The true time of inundation can be obscured if the loggers are launched with a long data recording interval. It is therefore important to balance the frequency of logger readings with the data capacity of the logger over the monitoring time period. Twelve minute intervals were adequate for our purposes in Oregon estuaries, but the interval between readings can be shortened for greater temporal accuracy.

The inundation signal may also be difficult to interpret if there is only a gradual temperature change (no abrupt signal). This can happen if a logger was gradually inundated, for example when the incoming tide peaks near the elevation of the temperature logger. Speed of inundation can be slow near peak tide; speed of inundation is usually more rapid during spring tide cycles, compared to neap tide cycles.

Conclusions and reminders

The temperature sensor method is a relatively low cost method for measuring the frequency and duration of tidal inundation without installing a series of water level loggers and conducting elevation surveys. The following guidelines will help you achieve optimum results when using the Method:

- If daytime solar warming tends to obscure the inundation signal, deploy temperature sensors during a period when the tides of interest are occurring at night. (Pilot deployments will help you determine whether this is necessary in your area.)
- If you use non-waterproof loggers like iButtons, you will need to waterproof them using a vacuum sealer or other method.

- The inundation signal is likely to be clearer with faster inundations, so when possible, monitor during higher high tides and spring tide cycles.
- Using shorter data recording intervals (e.g. 5min) will help detect the inundation signals on a finer scale. However, more frequent logging fills the logger's memory more rapidly.
- Visual observation can be used for a quick validation of the temperature logger method. For more rigorous validation, use a water level logger deployed near the temperature loggers. Once validated, the Method can be used in the same habitat types without further validation.
- Delays between the predicted time of inundation and the actual observed "inundation signal" provide valuable information on speed of water movement through a tidal channel system or across a large area.

For more information
Detailed information on the development of the Method can be found in Tully (2007) and in the full report from this project (Brophy *et al*. 2011).

References

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