Boat-Generated Wave and Turbidity Measurements: Connecticut River

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Abstract

Waves generated by high-speed recreational boats can play a significant role in bank erosion and failure along riverbanks. Frequent passes of these boats in confined channels increase suspended-sediment concentration and turbidity at relatively shallow water depths, and increase the erosion rate by wave breaking and long-shore currents. In the current study, boat-generated waves and turbidity were measured in the Connecticut River along a reach between Vernon Dam, Vernon, VT and French King Bridge, Miller Falls, MA. Two-meter-long self-powered, self-logging wave staffs were used to measure the water level and waves at three sites. Based on these uninterrupted measurements, boat-generated wave-characteristics were obtained for a period of four months between May 2015 and September 2015. As part of this study, turbidity and wave measurements at these three sites were carried out during a series of *in situ* experiments with a 5.7 m long tri-hull motorboat. The experiments included a total of 36 controlled passes parallel to the shoreline at speeds ranging from 8 km/h up to 55 km/h. Boat speed and path was measured with a GPS logger and the turbidity level near the bank was measured using two optical backscatter sensors. Relations between the wave height, wave period and turbidity level were investigated. This paper presents the results of these additional measurements and discusses relations between turbidity levels and boat-generated waves.

INTRODUCTION

Boat-generated waves can have significantly contribution to shoreline erosion and induce streambank failure. Due to the increasing popularity of recreational vessels, the contribution of boat-generated waves to bank erosion by increased boat traffic has become a bigger concern in navigable rivers. Measurements in Kenai River in Alaska showed that the energy transmitted to the banks from boat waves is up to 60% of energy of the streamflow (Maynord, 2008). Especially high-speed vessels are capable of producing sufficiently high waves that can cause significant damage to the riverbanks (MacDonald, 2005). Assessment of boat generate wave impact on the riverbanks requires the knowledge of the wave characteristics and associated erosion rates.

Figure 1. A high-speed boat operating near French King Bridge, MA.

The change in the turbidity levels can be related to the sediment suspension rate, and consequently indicate the amount of sediment disturbance (Hilton and Phillips 1982). Unfortunately, there are only a few studies that investigate turbidity levels in relation to boat generated wave properties in navigable rivers (Bauer et al. 2002; Göransson et al. 2014).

This study concerns field measurements of boat traffic and boat-generated wave properties in the Connecticut River (Figure 1). As part of this field study, *in situ* experiments were carried out to quantify the relationships between boat speed, boat wave properties, and the turbidity levels along the beach. The experiments included controlled passes near the wave loggers, at various speeds in the subcritical and supercritical range. The objectives of these experiments were to find out the correlation between the wave size, turbidity levels and boat speed, and to approximately define the order-of-magnitude relationships between these parameters. The results of this study provide insight and preliminary data for future detailed studies of field measurements of bank erosion induced by boat-generated waves.

FIELD SITES AND INSTRUMENTATION

Three field-monitoring sites were installed along the 32 km-long river reach of the Connecticut River between Vernon Dam (Hindsdale, NH) and Turner Falls Dam (Montague, MA) and used for long-term boat wave measurements. Figure 2 illustrates the locations of the sites along the river. The same monitoring sites were used for the field experiments. Two of the sites had one wave logger and the third site was equipped with two wave loggers. The wave loggers were held in place by a T-post driven into the riverbed near the bank at each site. The logger stations were chosen close the riverbanks with the objective to measure the boat-generated waves near the shore before they shoal and break. The wave loggers include a capacitance type wave staff and a battery powered microprocessor that stores the water level, and operated continuously at 30Hz frequency. Boat and wind generated waves in the study area were mostly in a frequency range of 0.2Hz - 2Hz. Thus, the 30Hz measurement frequency provided a fairly good temporal resolution, which is 15-readings-per-wave at the high frequency end of this range. Each logger had a 2-m-long staff providing a vertical resolution of approximately 0.5 mm.

Six time-lapse cameras were installed on three bridges along the river reach. The cameras were oriented in the streamwise direction and recorded at 10 s intervals. Camera recordings were used to visually supplement the wave analysis and to validate the boat signatures detected in the wave data.

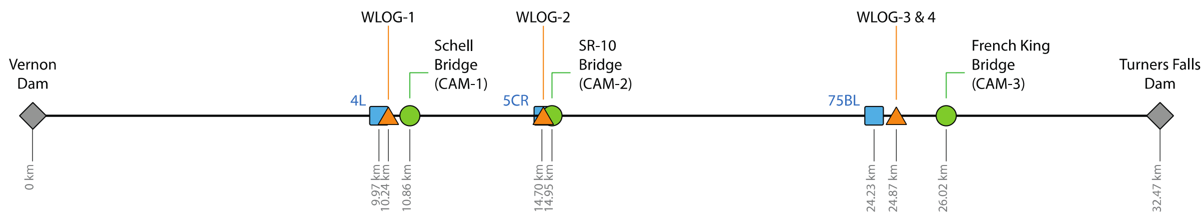

Figure 2. Boat monitoring site locations.

For the short-term field experiments, two turbidity meters (OSB-3+, Campbell Scientific Ltd.) were installed at each wave logger site. OSB-3+ is a near infrared laser backscatter turbidity sensor that can detect the suspended particles in water. Figure 3 shows the turbidity meter and wave logger configurations for WLOG-1 site. At each site two turbidity sensors were installed along a transect between the shoreline and the wave logger. One of the units was installed closer to the shoreline in the breaker zone, and the other one is attached to the wave logger holding structure. They were rotated sideways to avoid sediment accumulation on the optical element. Prior to the field measurements, the sensors were tested at the laboratory and configured to monitor the turbidity at 1Hz.

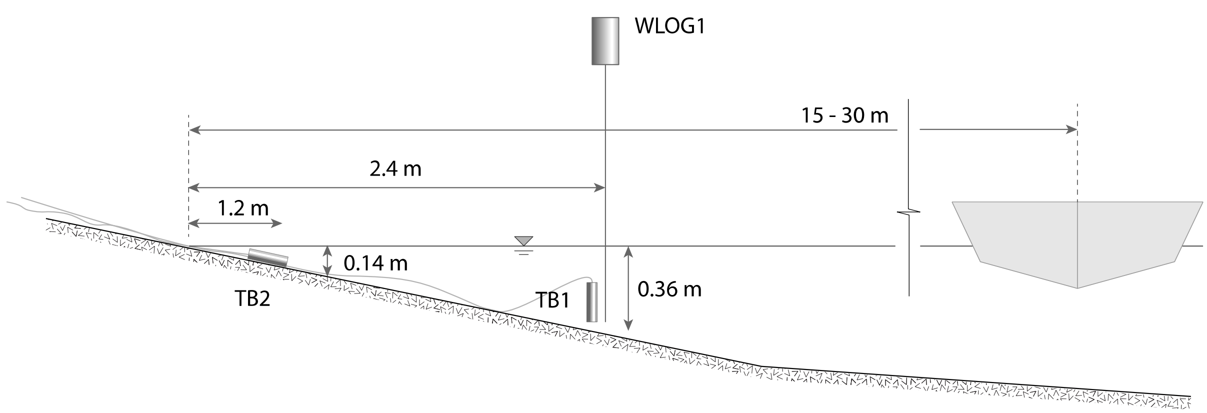

Figure 3. A typical transect at WLOG-1 site.

A 19-foot long Hurricane Sundeck Sport, a small size recreational vessel, was used during the field experiments. The boat was able to attain planning speeds up to 35 mph (15 m/s). Boat specifications are listed in Table 1, and a picture of the boat is shown in Figure 4. A handheld GPS unit was used to track the boat location and calculate the speed. The sapling rate was 1Hz.

Table 1. Boat specifications.

Hurricane 19-foot Sundeck Sport 188 IO	
Hull type	V-hull
Length	18 ft-10 in (5.74 m)
Beam	8 ft - 5 in (2.57 m)
Min. draft	1ft -1 in (0.33 m)
Weight	3,793 lbs (1,720 kg)
Dry weight	2,600 lbs (1179 kg)

Figure 4. A picture of the high-speed boat used during the experiments.

DATA ANALYSIS

Wave logger data is stored in an ASCII file containing the water surface elevation. The recorded data was converted to water depth and water surface elevations with a reference vertical datum (NAVD88, US feet) through RTK GPS survey of the loggers. The time series data was filtered to find low frequency variation of the mean water level using a low-pass IRR (internal impulse response) filter with a 10 s cut-off length. The unfiltered signal is normalized with the filtered signal to obtained water surface fluctuations. The high frequency ripples and noise are removed using another low-pass filter, of order 10 and cut-off length.

The time history of the frequencies of a transient boat wave signal was found using local time-frequency analysis. The windowed Fourier transform was used to identify the boat-generated waves in the recorded signal. The windowed Fourier transform divides the signal into segments, and each segment is transformed into Fourier space using a window-function. The time series signal is decomposed into its time-frequency-spectral density components, which is visually represented by a spectrogram. The spectrogram is a function of both the frequency and time since the decomposition is local. In the present case, the spectrogram is obtained using a Hamming windowed Fourier transform, of 512 (number of data points in the 30Hz signal) with 75% overlapping. Boat waves in the time series signal appear as short, low-to-high frequency chirps superposed into the random wind waves. This distinct characteristic was used to identify them in the recorded signal. The locations of the maximum wave heights and the wave frequencies associated those waves were obtained in each boat wave signal using zero-crossing analysis. Each wave is defined between two successive zero down-crossings in the normalized signal. The wave height is the difference between the maximum and minimum water surface displacement and the wave period is the time length of each wave.

The major steps of the wave data analysis and boat detection procedures are listed below:

- Filter and separate the water surface waves and mean water level using a low pass IRR filter.
- Apply windowed Fourier transform to find the spectrogram
- Find the mean spectral density of the low frequency band 0.05Hz-0.8Hz to filter the wind-generated waves.
- Remove low-frequency modulations mean spectral density
- Find the peaks and their locations mean spectrum time-series.
- Using zero-crossing analysis, calculate the wave height *H(t)* and wave period *T(t)* timer series.
- Find the peak zero-crossing wave heights H_{max} and wave periods T_{max}, nearest to t_{peak}.
- Compare the results with the time-lapse videos and remove any false detection.

Boat speed (ground speed) was calculated by numerical differentiation using the tracked locations.

RESULTS AND DISCUSSIONS

Figure 5 illustrates a typical wave signal and its spectrogram recording during the long-term boat wave measurements. The first plot is the mean water depth and water surface elevation (NAVD88, US Feet) on the secondary axis, the middle plot is the water surface displacement, significant wave height, the zero-crossing wave height, and the temperature (secondary axis), and the bottom plot is the spectrogram, which shows the spectral energy, frequency and time relationship. The temperature in the instrument enclosure was higher then the ambient temperature; therefore, temperature is overestimated during the day. The boats appear as short bursts in spectrogram and the their energy is widely distributed over a wide range of frequency, peaking around 1 Hz. The positions of the peaks are marked with '+' signs in both time series and spectrogram plots. Most of energy is concentrated around this frequency. The wind generate wave were less pronounced compared to the rest of the data recorded. The water depth was approximately constant at 3 m in this particular example.

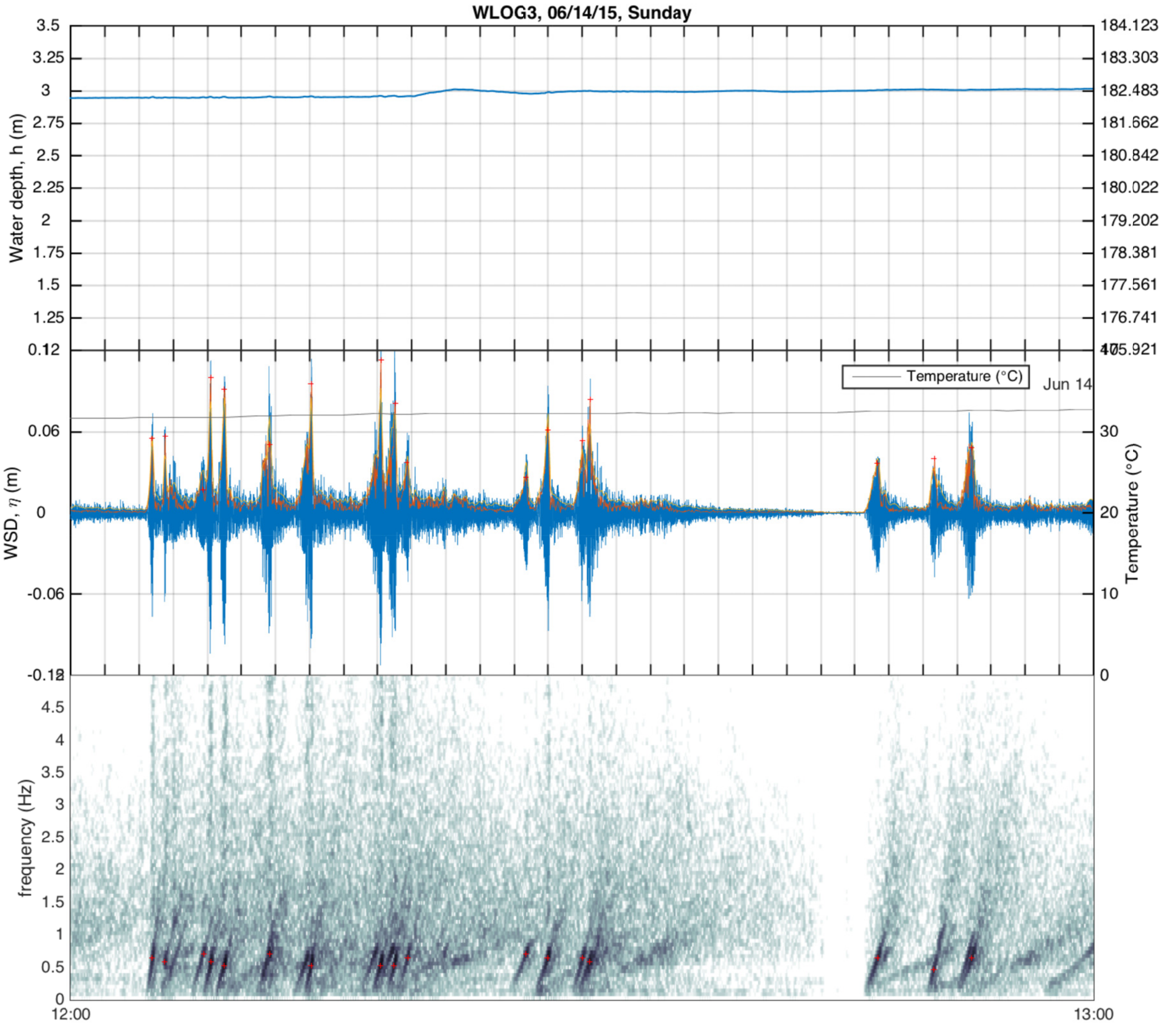

Figure 5. Recorded wave signal and its spectrogram on Jun 14, 2015, 12:00 pm – 1:00 pm at wave logger 3.

Distance from the logger was in the range of 15 m-30 m at WLOG1, 20 m-30 m at WLOG2 and 20 m-40 m at WLOG3 & WLOG4. The boat passes included speeds ranging between 5 mph (8 km/h) up to 34 mph (55 km/h) in both upstream and downstream directions. Each speed is repeated twice, one in the upstream direction and the other one in the downstream direction. Figure 5a, shows the aerial picture and the recorded tracks at WLOG1 site. The aerial photo shows the scattering of the tracks for each pass. The differences in the measured waves are compared for tracks of similar speeds. It was concluded that, the errors due to wave dispersion is much less than the changes in the wave properties at different boat speeds. Figure 6b and 6c shows two frames during a typical experiment, when the boat is approaching to the instrument station (6a), and when the largest wave reached to the shore after 25 seconds (6b). The mild slope of the riverbank indicates an established beach profile, which is shaped by the waves, similar to the plunging breaker in Figure 6c. The weather was calm during the experiments at all three sites, and wind noise in the recorded data was essentially zero.

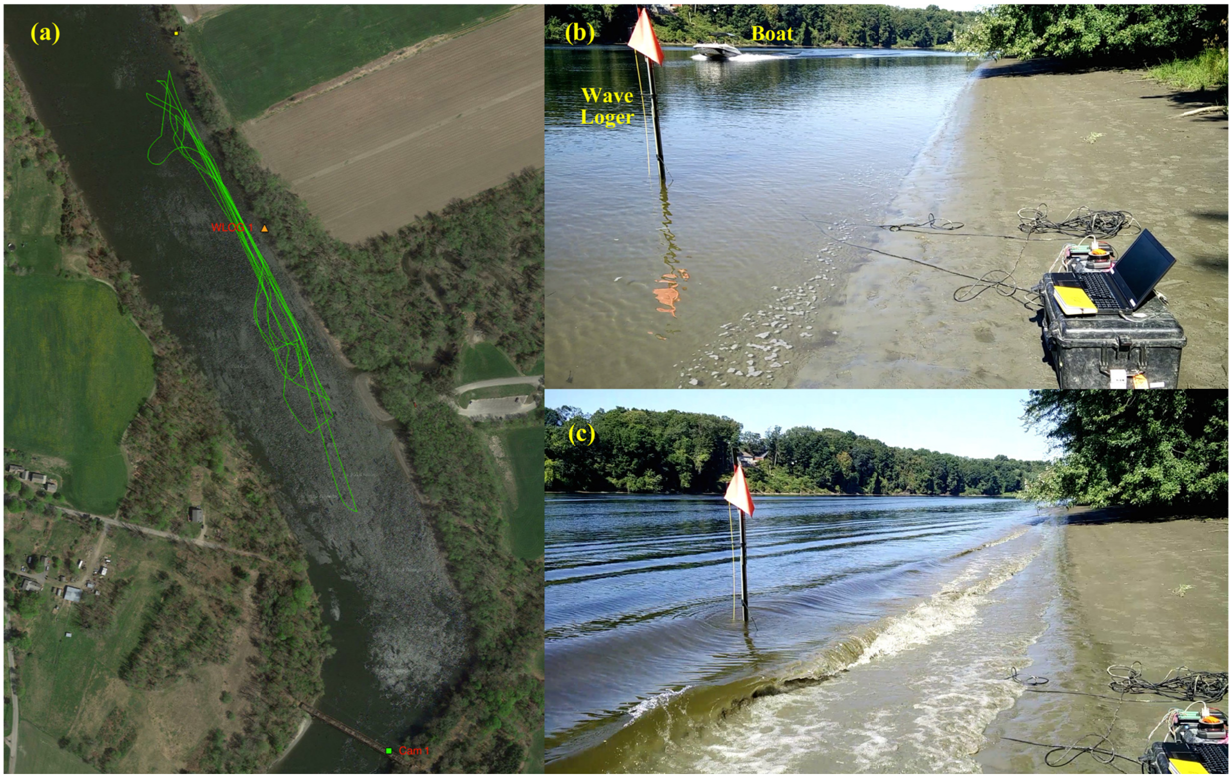

Figure 6. (a) Boat tracks at WLOG-1 site, and field experiments (b) when the boat is approaching and (c) shortly after the boats pass.

The measured turbidity, water surface displacement and boat speed are compared for WLOG-1 site in Figure 7. Turbidities are given in Nephelometric Turbidity Units (NTU). The turbidity measured WLOG1 shown in Figure 7 is much higher then the other two sites because, at the WLOG1 site, the turbidity metes were relatively closer to the shore, and the water was considerably shallower at the turbidity meter locations, compared to the other two sites. Also the beach slope was milder at WLOG1 site.

Using these measurements, peak speed for each pass, peak turbidity at TP1, and maximum H_{max} are extracted and plotted in Figure 8. The average trend lines in each plot are also shown as dashed lines. The first plot in Figure 8 compares the maximum wave height and the peak turbidity level recoded at TB1. TB2 measurements are not included in these figures. Despite some expected dispersion in the data, the turbidity increases with increasing maximum wave height.

The second plot in Figure 8 shows the variation of the maximum wave height at various boat speeds. In all three sets of experiments, the wave height increases with the increasing boat speed in the subcritical non-planning range. When the boat planes, the maximum wave height starts decreasing with a milder slope compared to the increasing trend. The peak is the critical speed and corresponds to Froude number equal to unity. The dispersion in the data is possibly due to the variations of the distances of the tracks from the wave logger. Boat speeds in these plots refer to ground speeds since there are calculated using GPS data. The speed relative to the flow varies depending on the direction of the boat track.

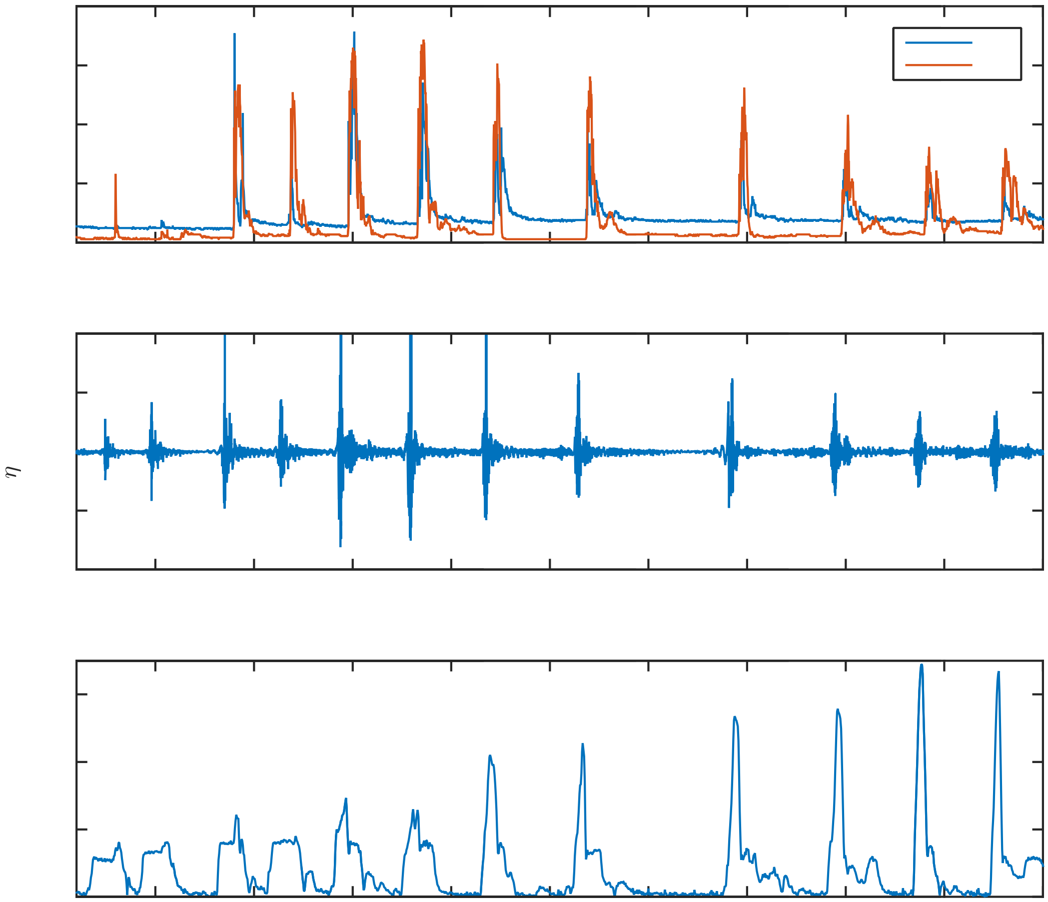

Figure 7. Turbidity, water level and boat speed time series at WLOG1 site.

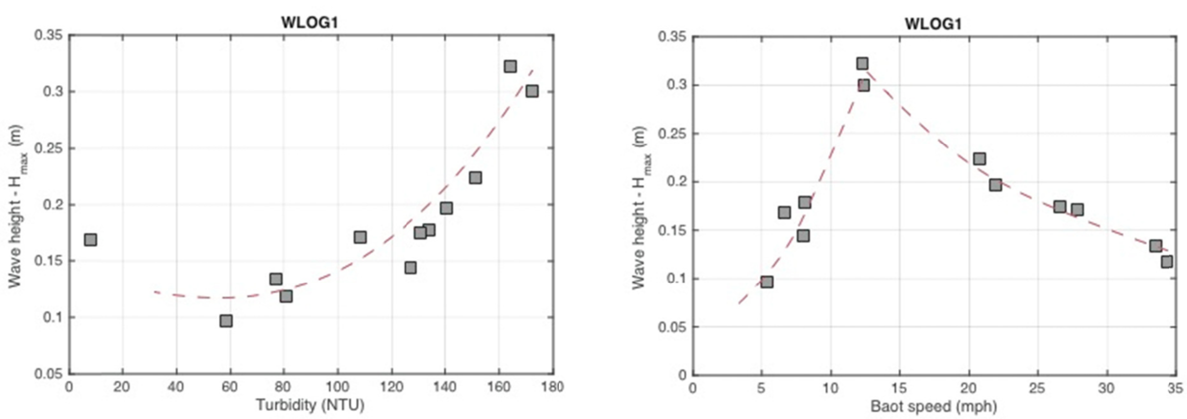

Figure 8. Comparison of wave height at various bot speeds at WLOG1 site.

CONCLUSIONS AND FUTURE WORK

Three boat and wave-monitoring stations were installed at three locations along the reach of Connecticut River between Vernon Dam and turner Falls Dam. The stations consisted of wave loggers and time-lapse cameras. Continuous wave data was collected for over four months between May and September of 2015. A chirp detection method was used to identify boats and wave properties. The data was used to obtain boat traffic and wave statistics at the tree sites. Turbidity was measured at the three sites during a set of controlled boat passes.

The measurements showed that the measured turbidity near the shore increased with increasing boat speed. At planning speeds, even though the maximum wave height is lower than the critical value, the measured turbidity increased. Previous laboratory experiments with the same instruments in mixtures of water and silty sediments at various concentrations showed that there is a linear relation between the turbidity level and suspended sediment concentration. These preliminary experiments reveal that boat generated waves at near critical speed can significantly increase the suspended sediment concentration near the shoreline. Additional work is needed to establish the relations between the turbidity level and suspended sediment

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