PREDICTING SCOUR AND MAXIMUM SETTLING DEPTHS OF SHIPWRECKS: A NUMERIC SIMULATION OF THE FATE OF *QUEEN ANNE'S REVENGE*

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Abstract: Measurements of varying wave energy events were fed into a scour model to examine the fate of several seafloor artifacts related to the wreck of *Queen Anne's Revenge*. Comparison between model estimates and the observed state of the artifacts suggest that maximum settling depth is controlled both by the magnitude of near-bed flow and the characteristics of the underlying sediments. The results from this study suggest that numerical forecasts of wave conditions might be used to predict the settling depth and exposure of important historical artifacts.

INTRODUCTION

The discovery of an early 18th century shipwreck near Beaufort Inlet, North Carolina, believed to be the pirate Blackbeard's flagship *Queen Anne's Revenge (QAR)*, affords an incredible opportunity to examine the long-term fate of artifacts in an energetic, shallow-water setting. The ship, which ran aground in waters less than 4 m deep while attempting to navigate Beaufort Inlet, now rests in 7 m of water on the shoals of the ebb tidal delta. Archaeological evidence indicates the wreck has remained in the same location since the initial grounding which suggests that the numerous and varying-sized artifacts scattered around the debris field have settled through approximately 3.5 m of substrate. McNinch *et al* (2001) hypothesized that this extensive settling through unconsolidated sandy sediment resulted from episodic periods of scour and burial, and that the wreck's recent exposure occurred because the sedimentologic nature of the underlying geology limited continued scour. In this study, we utilize an analytical model designed for predicting scour around objects on the seafloor to test the episodic scour-settling hypothesis and to evaluate the model's utility as a basis for a refined model that predicts scour and maximum settling depths over long periods and with varying geologic strata. Specifically, a model that has successfully predicted the scour and settling of mines is applied to previously measured boundary conditions at the *QAR* wreck site and results are evaluated from seafloor and sub-bottom surveys as well as from the location and characteristics of artifacts. We believe a simple model that predicts scour and maximum settling depths over long periods will be an extremely valuable tool for the management and recovery of shipwrecks or other artifacts of cultural significance.

Queen Anne's Revenge, formerly the French slave ship *Concorde*, was a three-masted ship of approximately 250-tons (Moore, 1997) with a keel depth that likely extended 3.7 m below the surface of the water (Moore, personal communication). Written documentation by David Harriot, who sailed with Blackbeard, noted that the *QAR* "ran aground" on the shoals of the ebb tidal delta while attempting to enter Beaufort Inlet in 1718 (Moore, 1997). Beaufort Inlet,

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a barrier island tidal inlet, has remained open and navigable since at least 1585 (Fisher, 1962). Consistent channel depths of 5 m has fostered maritime traffic since the late 17th century but the dynamic nature of the ebb channel position (Wells and McNinch, 2001) as well as conditions across the shallow portions of the ebb tidal delta can be quite treacherous for deep-drafted vessels attempting to navigate the region. Observations of currents and waves, seafloor bathymetry, and analysis of historic charts suggest that the wreck is periodically exposed to considerable energy (McNinch *et al*, 2001). The main inlet channel appears to have migrated across the site numerous times since 1718, and its strong currents have eroded the surrounding seafloor to depths of at least 5-6 m (Wells and McNinch, 2001). Near-bottom currents and waves were measured over a nearly-continuous interval of two years and, fortuitously, captured the effects of a hurricane, a nor'easter, a sou'wester, and intervening periods of fair weather. Estimates of sediment transport reveal that sediment is stable under fair-weather and moderate storm conditions, but that a significant volume of sediment is mobilized when wave heights exceed 1.5 m.

QAR artifacts have been mapped on the southwestern flank of the ebb tidal delta and are scattered over a 30 x 50 m area. Interestingly, from the perspective of this work, all of the artifacts appear to rest on the same depth horizon (within 50 cm), although the largest pieces are typically more exposed above the seafloor surface. The wreck site includes a large rubble mound measuring approximately 5x10 m that includes the lower portion of the hull and a hosts of artifacts such as canons, ballast stones, and anchors all of which have become concreted into one indistinct mass (Figure 1A). Smaller mounds encasing canons, anchors, canon balls etc. that were likely separated from the vessel at the time of sinking litter the perimeter of the main rubble mound and lie at varying states of exposure on the seafloor or within 50 cm of the surface (Figure 1B). Given that the area around the wreck site has undergone considerable erosion

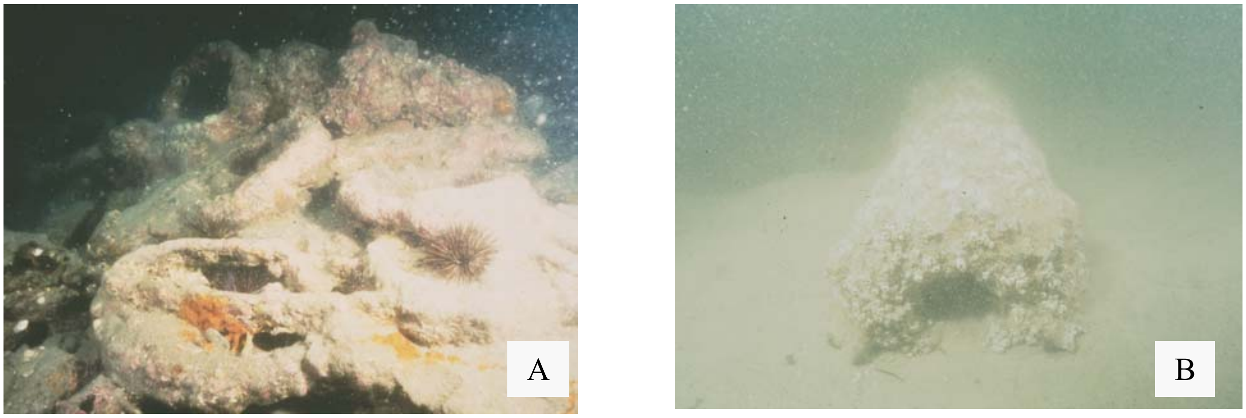

Figure 1. Underwater photographs of the concreted, main rubble mound exposed on the seafloor surface (A), and an individual canon (B) from the *Queen Anne's Revenge* wreck (courtesy of the NC Underwater Archaeology Unit).

related to a combination of waves, currents, and a migrating ebb channel, we were fascinated and intrigued that artifacts of different size and mass were all found resting on the same horizon after almost 300 years on the bottom. Remarkably, evidence ranging from the relatively unspoiled condition of the bottom timbers, location of all the artifacts at roughly the same depth horizon, and young encrusting coral (less than 15 years old; N. Lindquist, personal communication) all suggest that a process which preserves the artifacts through burial and maintains an equal rate of settling regardless of size has been operating. McNinch *et al* (2001) hypothesized that basic principles of seafloor scour may explain these observations but could only speculate as to whether scour occurred evenly between different sized artifacts and under varying hydrodynamic conditions. Numerical simulations with a proven scour model DRAMBUIE (Whitehouse, 1998; Friedrichs, 2002) combined with direct observations from the *QAR* site allow us to evaluate this hypothesis.

The DRAMBUIE model utilizes a simple relationship for rates of energetic scour and burial:

$$S = S_{inf}(1 - exp(t/T)), \tag{1}$$

where S_{inf} is the final depth of scour (about 1.2 diameters of the structure), t is time, and T is a time-scale factor which, in turn, is a function of dimensionless numbers characterizing the environmental forcing. The rate of scour for a cylinder is given by (1) with

$$S_{inf} = 0 \text{ for } U_c < 0.75\, U_{cr}, \tag{2a}$$

$$S_{inf} = 1.15\, D\, (2\, U_c - 1.5\, U_{cr})/U_{cr} \text{ for } 0.75\, U_{cr} \le U_c < 1.25\, U_{cr}, \tag{2b}$$

$$S_{inf} = 1.15\, D \text{ for } U_c \ge 1.25\, U_{cr} \tag{2c}$$

where D is the cylinder diameter, U_c is the characteristic velocity above the object (either uni-directional, oscillatory or combined), and U_{cr} is the critical velocity for the initiation of motion of non-cohesive sand as a function of sand size and density. The time-scale factor in (1) is given by

$$T = 0.095\, q^{-2.02}\, D^2\, [g(s-1)d^3)]^{-1/2}, \tag{3}$$

where $q = u_*^2\, [g(s-1)d]^{-1}$ is the Shield's parameter, g is the acceleration of gravity, s is the submerged weight of sand relative to water, d is grain size, and u_* is the skin-friction shear velocity.

Other observations suggest a cylindrical mine on a sandy inner shelf buries by repeatedly falling into its own scour pit (Whitehouse, 1998; Briggs *et al*, 2002; Friedrichs, 2002). We hypothesize that the same mechanism occurs in the case of artifacts lying on the seafloor. The depth of burial of a shipwreck relative to the undisturbed surrounding bed is given approximately by the maximum depth of scour, S_{max}, experienced to that point by the wreck. Instantaneous burial depth, B, is defined as

$$B = S_{max}\, [1 - e(S/S_{max})] \tag{4}$$

where e is a factor (between 0 and 1) that parameterizes the efficiency with which scour re-exposes the wreck while the wreck simultaneously settles into its own scour pit.

METHODS AND RESULTS

Field Observations

Numerous swath bathymetry and side scan sonar surveys were collected at the *QAR* site from 1999 to 2002 utilizing an interferometric (Submetrix 234 kHz) swath sonar system integrated with a motion sensor and a real-time kinematic global positioning system. These surveys were consistent with diver observations that noted continued exposure of the main rubble mound, extending approximately 1-2 m above the seafloor surface, along with scour excavations around the mound. McNinch *et al* (2001) documented the excavation of a large tear-dropped shaped scour depression in the lee of the mound following hurricane Bonnie. More recent surveys show, however, that the mound continues to remain exposed above the seafloor and has not settled a measurable distance into the depression. Figure 2 shows a 3-dimensional view of side scan sonar backscatter overlying swath bathymetry. The concretions of the artifacts create a strong backscatter signal, inverted and expressed as white, and can be seen elevated above the surrounding seafloor with a linear scour depression visible in the background immediately behind the mound. Diver observations and our surveys also show that the area is covered ephemerally with fine sand and silt, which settles from the water column and drapes the rubble mound and fills the scour depressions. Large-scale sandy bedforms have also been seen to migrate through the area and temporally cover some of the artifacts and previous scour excavations.

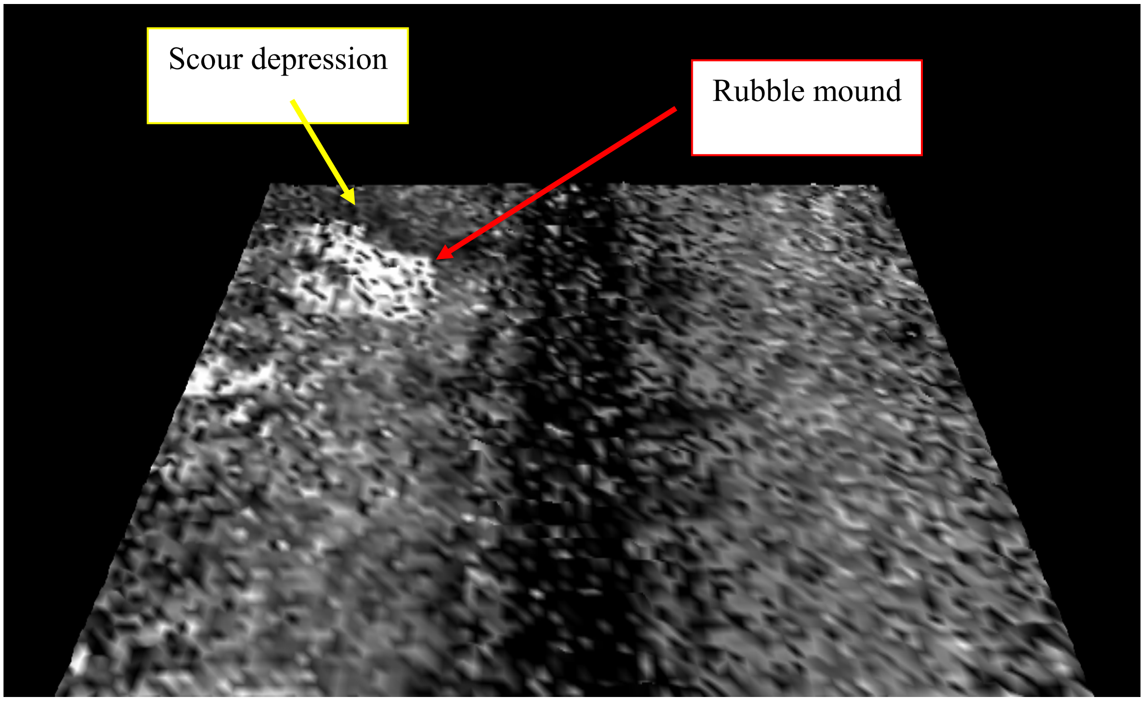

Figure 2. Three-dimensional view of side scan sonar backscatter draped over swath bathymetry showing the main rubble mound and adjacent scour depression.

Many attempts were made to collect vibracores from around the wreck site and directly beneath the main rubble mound. A large Alpine vibracoring system obtained nine cores but none of them penetrated more than 1.5 m below the seafloor surface, terminating on a stiff, well sorted silty sand. Smaller diver-held vibracores, used to core beneath the mound, also met refusal roughly 1 m below the surface. Preliminary analyses of the cores and diver observations during archaeological trenching reveal three distinct substrates (Figure 3). The surface sediment varies in thickness from 0 to 1 m and is a poorly sorted fine to medium sand with fine shell hash. Beneath the surface sand is a very poorly sorted sand and coarse shell layer that contains most of the artifacts (Wilde-Ramsing, personal communication). The layer beneath the shelly substrate is a very well sorted, grey silty sand that is stiff and slightly cohesive. Archaeologist report that this substrate is culturally sterile; all artifacts are found above this layer. We suspect that not only is this lower substrate difficult to core, its cohesive properties likely make it resistant to erosion and thereby serves as a boundary to further scour. The side scan sonar surveys show exposure of the coarse shell layer in bathymetric lows around the site. The coarse material, presumably the shell fraction, appears to be reworked by waves into large wave ripples and are thus quite visible in the side scan record (Figure 4). We suspect that the shell layer underlies much of the area and likely represents a relict channel lag when the ebb channel was located at the site.

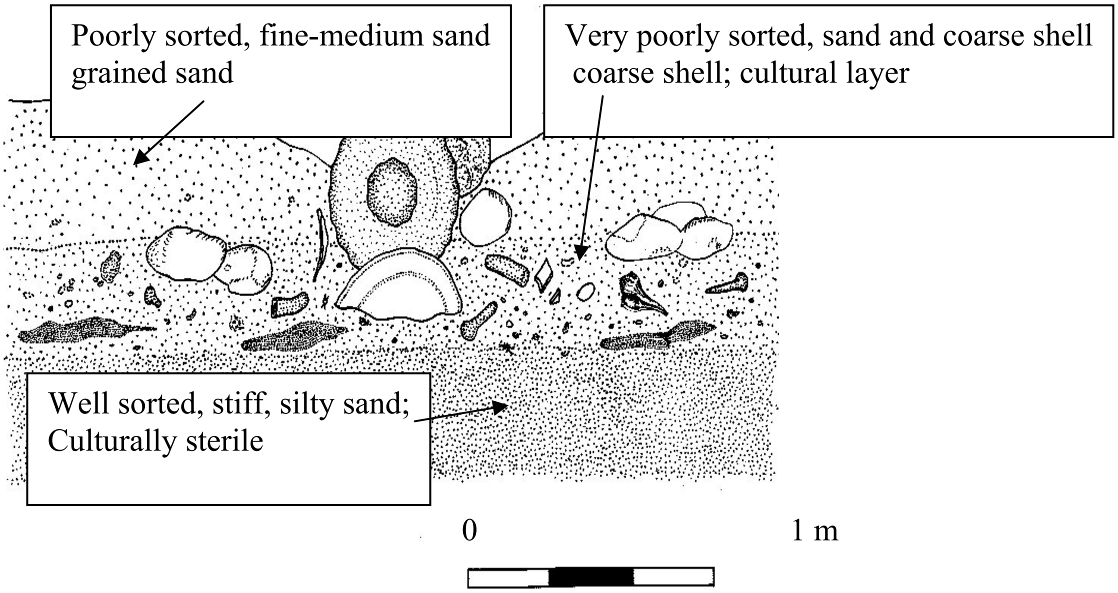

Figure 3: Diagrammatic cross-section of substrates and relative location of artifacts found at canon #2 (courtesy of NC Underwater Archaeology Unit, M. Wilde-Ramsing).

An electromagnetic current meter with integrated pressure sensor, InterOcean S-4A, was deployed approximately 15 m southwest of the main rubble mound to provide information on waves and currents near the wreck. The meter was rigidly mounted to a stand that held the sensors 1 m above the bottom. Measurements of pressure and flow were collected at 2 Hz for 12 minutes every hour and continued for 298 days from May 1998 to April 1999.

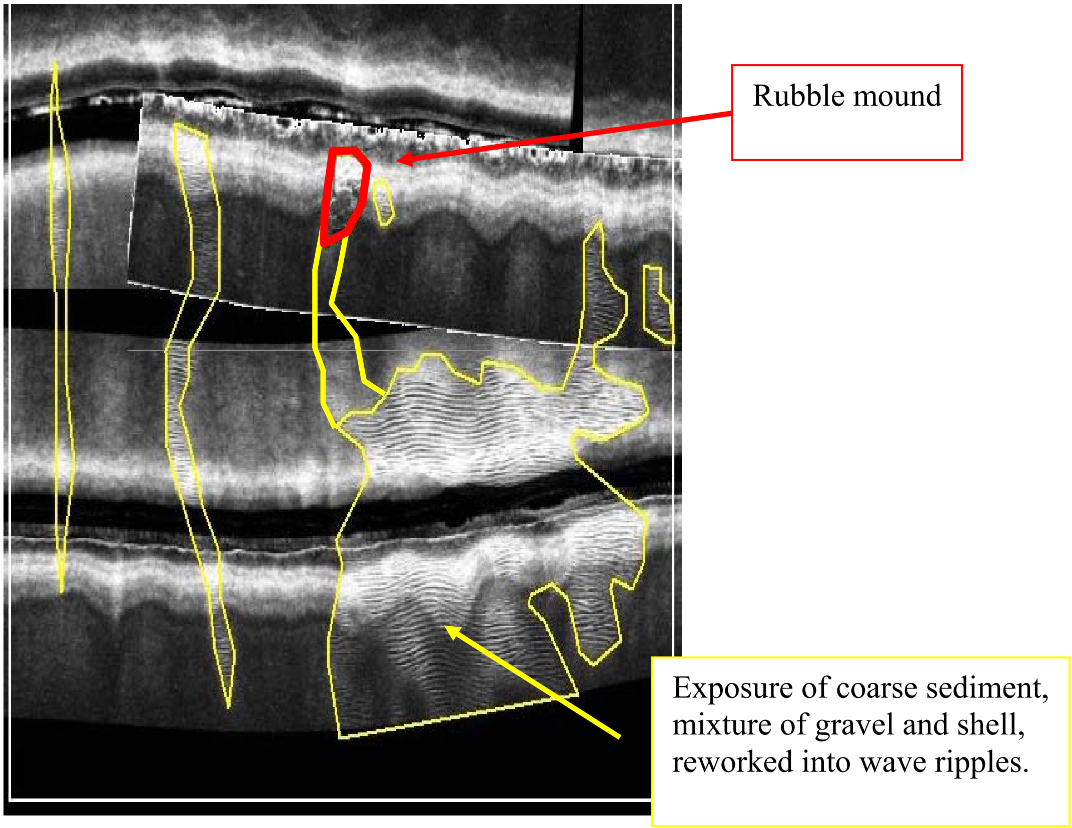

Figure 4. Side scan sonar mosaic (Marine Sonics 900 kHz) showing the outcrops of coarse shell sediment reworked into wave ripples and the surrounding fine sand relative to the main rubble mound.

Model Simulations

We have chosen to use the scour equations of Whitehouse (1998) because of their reliance on well-established engineering relations for scour around seabed objects. The Whitehouse relationships form the basis of the mine burial model DRAMBUIE (Friedrichs 2001). This study, therefore, represents an application of DRAMBUIE to the case of submarine archaeological artifacts. For purposes of this experiment, three artifacts with distinctly different sizes were modeled, namely a canon ball, a canon, and the main rubble mound of the *QAR* wreck site. Four distinct wave condition episodes, a tropical hurricane, an extratropical winter storm (Nor'easter), a series of sustained southwesterly winds (Sou'wester), and a fair weather period, were culled from two years of observed near bed velocities and fed into the model to predict the resulting scour and burial. Each model run was treated separately assuming each artifact was initially at rest on the surface of the seabed. The resulting scour depths were then compared to the observed condition of the wreck artifacts and used to assess the role of underlying geology on artifact resting depth. The key environmental parameters to the model when applied to the shipwreck were near bed orbital velocity, sand size, diameter of the object, and time. Orbital velocity was set by each time series dataset. A D_{50} grain size of 0.19 mm (fine sand) was chosen based on previous sediment samples from the fine sand plain surrounding the *QAR* mound (McNinch *et al*, 2001). The representative diameter for each artifact (0.15, 0.25, and 2 m respectively) were based on archaeological analysis of the wreck site (Wilde-Ramsing, personal communication)

The input of orbital velocity into the DRAMBUIE model can come either in the form of direct near bed measurements (Ub_{ob}) or from predictions of near bed orbital velocity (Ub_{LWT}). In order to generate the later estimates, first significant wave height (Hs) and peak wave period (Tp) were determined from spectral analysis of the time series of pressure data recorded by the S4 current meter, following the approach of McNinch *et al* (2001). Next, near bed orbital velocities were estimated by applying linear wave theory to the wave height (Hs) and period (Tp) values using the solution from linear wave theory (LWT) for horizontal velocity of a linear progressive wave (Dean and Dalrymple, 1991)

$$Ub = \frac{\pi H}{T}\frac{cosh(h+z)}{sinh(kh)}cos(kx - wt) \quad . \tag{5}$$

In this study, Ub_{LWT} was chosen over Ub_{ob} for several reasons. First, as will be shown in the results, linear wave theory estimates (Ub_{LWT}) were in close agreement to the observed values (Ub_{ob}). The Ub_{LWT} values, in fact, represent slightly conservative estimates of near bed flow conditions. Secondly, by utilizing time series of wave height and period, the possibility exists for using global wave forecast models such as the Wave Watch 3 (*WW3*) model to predict real-time scour conditions for the *QAR* wreck and other similar sites in the absence of bed mounted instruments. A similar scour prediction approach has recently met with success in being able to use forecasts of environmental conditions to predict scour-related burial of seabed mines (Briggs *et al*, 2002). One of the anticipated products of this study is the development of an operational model of artifact related scour burial that could be utilized by marine archaeologists in finding wreck sites and estimating their exposure to decay.

Wave Conditions

The time series of wave height (Hs) and period (Tp) for each of the four separate forcing cases is shown in Figure 5.

Hurricane Bonnie

The most energetic wave case was observed during hurricane Bonnie. Wave height ranged from 0.25 - 3 m with a mean of 1 m. Peak wave periods ranged from 5-17 s with a mean of 10 s. For more than 90 hours waves exceeded 1 m in height with periods between 10-17 s. At the peak portion of the storm, significant wave height was greater than 3 m with peak spectral period of 15 s.

Southwesterly Winds

The second test case comprised a period of persistent southwesterly winds (Sou'wester). During this period, wave heights were between 0.2 – 1.1 m with a mean of 0.5 m. Wave periods varied between 5 – 11 s with a mean of 7 s. Wave heights exceeded 1 m at two times with attendant wave periods of approximately 7 s.

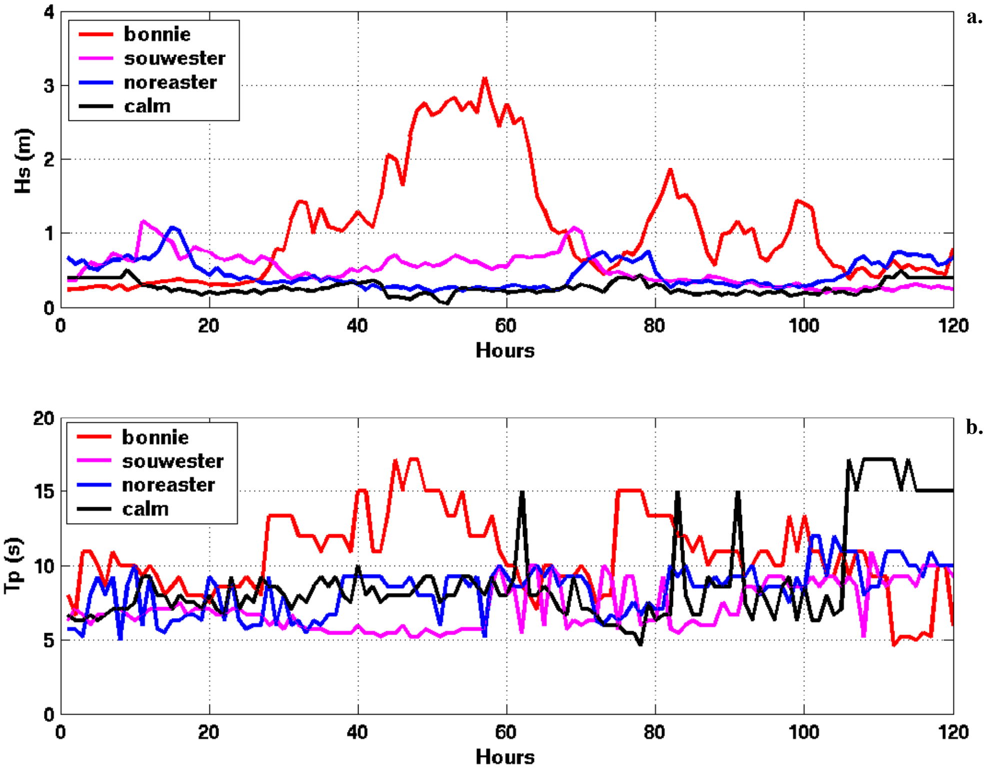

Figure 5. Oceanographic conditions at 3 hour intervals for the *Queen Anne's Revenge* site off of Beaufort Inlet, NC under four wave conditions observed with an S4 current meter. (a) Significant wave height in meters. (b) Peak spectral period in seconds.

Nor'easter

Due to the orientation of the coastline around Beaufort Inlet and the sheltering protection of Cape Lookout, extratropical winter storms (Nor'easters) have a somewhat limited impact on this site (McNinch *et al*, 2001). The Nor'easter recorded in this data set was no exception and thus represented the third most energetic model wave case. In this dataset, wave height ranged from 0.2 – 1.1 m with a mean of .44 m. Wave periods were between 5 – 12 s with a mean of 8.3 s. Wave period and wave height ranged from 5 – 12 seconds and 0.5 – 0.75 m respectively. One brief episode included a wave height of ~1 m and period of 7 s.

Fair Weather

The fair weather case was the least energetic condition tested, comprising a period of very calm and essentially negligible wave conditions. Wave height ranged from 0.05 – 0.5 m with a mean of 0.25 m. Wave period varied between 5 – 17 s mean of 9 s.

Figure 6 shows a comparison of measured (Ub_{ob}) and estimated (Ub_{LWT}) orbital velocities. There is good agreement between the two with Ub_{LWT} frequently providing a more conservative estimate of the measured conditions. Similar studies (Briggs *et al*, 2002) have used linear regression to improve the fit between observed and LWT derived near bed orbital velocities.

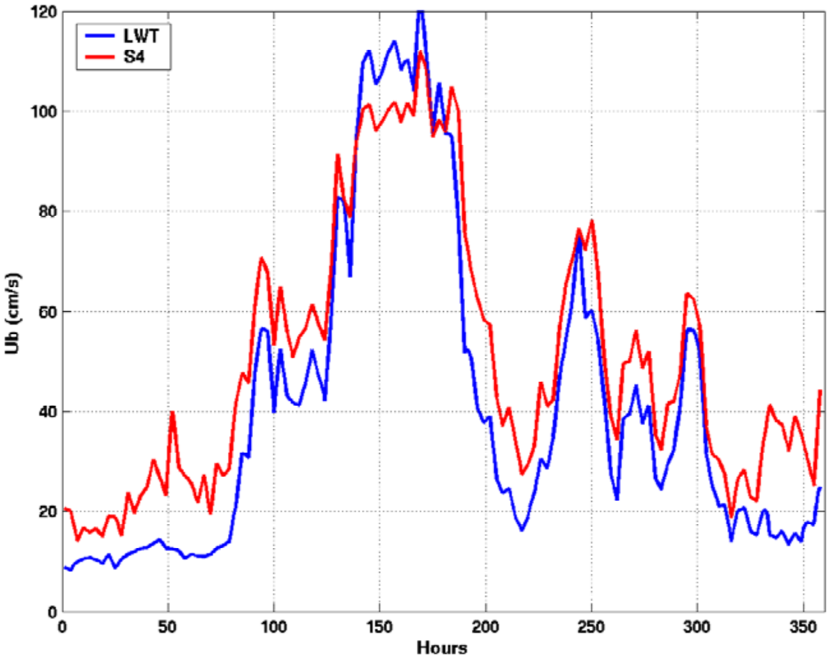

Figure 6. Comparison of two estimates of near bed orbital velocity (in cm/s) during the passage of hurricane Bonnie. Linear wave theory (LWT) derived estimate (blue) and S4 current meter directly measured value (red).

Scour Predictions

The time series of scour depth (in cm) for each of the artifacts during all four wave cases are shown in Figure 7 and summarized in Table 1.

Hurricane Bonnie

The DRAMBUIE model predicts complete scour and burial of all three artifacts based on the forcing conditions of hurricane Bonnie (Figure 7a). The peak portion of the storm initially induces scours around all three artifacts, which are subsequently buried during the waning portion of the storm. A second energetic wave event then partially re-exposes the objects before they are buried again.

Southwesterly Winds

The test case with southwesterly waves resulted in mixed scour conditions for the three artifacts (Figure 7b). As in the case of hurricane Bonnie, both the canon ball and the canon were predicted to undergo complete scour burial. The conditions, however, were not sufficiently energetic to induce complete scour of the large rubble mound. The rubble mound was predicted to receive only around 40 cm of scour.

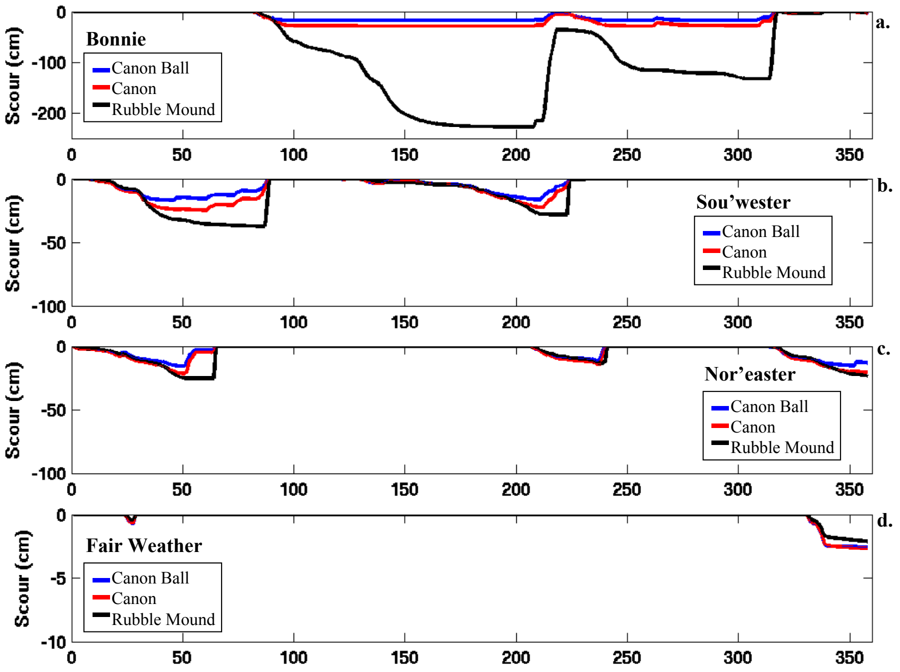

Figure 7. Predicted scour depth (in cm) for *QAR* artifacts canon ball (blue), canon (red), and rubble mound (black). (a) Tropical hurricane Bonnie. (b) Persistent Southwesterly Winds. (c) Extra-tropical Nor'easter. (d) Fair weather. *Note the change in vertical scale between plots a/b, c, and d.

Nor'easter

The Nor'easter test case included three separate scour episodes. The canon ball was predicted to undergo complete scour and burial from each episode. The model suggests that the nor'easter would produce near total scour for the canon with a maximum scour depth of 21 cm (84%). The waves in this case were only capable of scouring the rubble mound to a minor depth of 25 cm (12.5%).

Fair Weather

The mild waves of the fair weather period produced negligible scour (< 3 cm) in the case of all three artifacts.

Table 1. Summary of Scour Model Results for *QAR* Artifacts Under Four Wave Cases

Artifact	**Diameter (m)**	**Hurricane Bonnie**	**SouÕwester**	**NorÕeaster**	**Fair weather**
Cannon ball	**0.15**	**Complete scour burial**	**Complete scour burial**	**Complete scour burial**	**Negligible scour burial**
Cannon	**0.25**	**Complete scour burial**	**Complete scour burial**	**Near complete scour burial**	**Negligible scour burial**
Rubble Mound	**2**	**Complete scour burial**	**Moderate scour burial**	**Minor scour burial**	**Negligible scour burial**

DISCUSSION AND CONCLUSIONS

In short, field observations show 1) partial exposure of the main rubble mound above the seafloor 2) scour depressions activated during storms with substantial waves but negligible settling of the main rubble mound, 3) smaller, individual artifacts at varying levels of exposure, yet all lying on roughly the same depth horizon, and 4) most importantly, all artifacts have been discovered in a coarse, shell layer lying directly above an erosion-resistant, stiff silty sand. Results from the model simulations, we believe, are consistent with field observations and support the episodic scour-settling hypothesis. The three objects used in this model study (canon ball, canon, and rubble mound) were seen to succumb to varying degrees of burial under conditions ranging from fair weather to severe storms. Although varying burial rates by themselves will likely leave the objects at different levels in the seabed at any given instant in time, over the long-term occasional severe events would reset the artifact depths to a normalized horizon relative to the surrounding seafloor. Simply put, a large storm event such as the direct passage of a hurricane would wipe out the record of previously minor events leaving artifacts at a depth in the seabed in direct adjustment to the hurricane conditions. Scour alone cannot excavate an artifact through layers of fine sand deeper than the size of the object itself, since once the artifact has settled and no longer protrudes above the surrounding seafloor the scour mechanism shuts off. The tops of all the artifacts, including the main rubble mound, will therefore reach the same depth horizon episodically whenever a severe wave event occurs at the site.

A significant contradiction between the scour model simulation and the actual resting depth of the main rubble mound is apparent following hurricane Bonnie. The model predicts full scour (2 m) and subsequent settling and burial, whereas the rubble mound has remained perched above the seafloor throughout the years of observation. We believe this discrepancy occurs because the rubble mound is resting on a more scour resistant layer, the cohesive silty sand, and continued excavation is unlikely even under the most severe wave conditions. As suggested conceptually by McNinch *et al* (2001), the maximum settling depth appears to be controlled by the magnitude of near-bottom currents and the characteristics of the underlying sediment. Our results suggests that, indeed, the fate of artifacts in any environment can be predicted with knowledge of the current regime and the underlying stratigraphy. If an erosion resistant layer is present at a depth in which currents remain strong, the artifacts will likely become exposed on this layer and eventually be transported away or be exposed to degradation, depending on the size and transportability of the artifacts. We believe this may explain the many anecdotal stories of wrecks suddenly appearing on beaches following a severe storm decades or centuries after the vessel sank. If a wreck occurred in the outer surf zone, remains would quickly scour and settle into the sandy substrate. Episodic erosion of the surrounding seafloor would gradually cause the remains to settle in-place to a lower and lower horizon until either it reached a depth in which currents were no longer strong enough to scour or it encountered an erosion-resistant layer in which case it would gradually degrade in-place or possibly be transported shoreward and left on the beach.

These results suggest that the DRAMBUIE model can be successfully used to predict the maximum settling depth of artifacts when near-bed currents and underlying sediment characteristics are known. Future work will test whether simply wind information and wave hindcasting can be utilized, in lieu of expensive current meter deployments, along with integrating measured geologic substrates to provide a robust and user-friendly numerical model for predicting the long-term fate of artifacts in shallow-water settings.

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REFERENCES

Briggs, K. B., Elmore, P., Friedrichs, C. T., Traykovski, P., and Richardson, M. D., 2002. Predicting Mine Burial at the Martha's Vineyard Coastal Observatory. Eos Trans. AGU, 83(47), Fall Meet. Suppl., Abstract OS61A-0185, 2002.

Dean, R.G., and Dalrymple, R.A., 1991. *Water Wave Mechanics for Engineers and Scientists*. World Scientific Press, Inc. Singapore, 353 pp.

Fisher, J.J., 1962, Geomorphic expression of former Inlets along the Outer Banks of North Carolina, Masters Thesis, UNC-CH, 120 pp.

Friedrichs, C.T., 2002. Existing simple models for mine burial in sand by wave scour. Presented at the ONR Mine Burial Prediction Modeling Workshop.

Lindquist, N., 1999, personal communication, Institute of Marine Sciences, UNC-CH, Morehead City, NC.

McNinch, J.E., Wells, J.T., and T.G. Drake, The fate of artifacts in an energetic, shallow-water environment: scour and burial at the wreck site of Queen Anne’s Revenge, *Southeastern Geology*, v. 40, No. 1, p. 19-27.

Moore, D., 1997, Blackbeard the pirate: historical background and the Beaufort Inlet shipwrecks, *Tributaries*, No. 7, p. 31-39.

Moore, D., 1999, personal communication, Beaufort Maritime Museum, Beaufort, NC.

Wells, J.T. and McNinch, J.E., Reconstructing shoal and channel configuration in Beaufort Inlet: 300 years of change at the site of Queen Anne’s Revenge, *Southeastern Geology*, v. 40, No. 1, p. 11-18.

Whitehouse, R., 1998. Scour at Marine Structures: A Manual for Practical Applications. Thomas Telford Publications, London, 198 p.

Wilde-Ramsing, M., 2002, personal communication, North Carolina Underwater Archaeology Unit, Morehead City, NC.

KEYWORDS

Marine archaeology, Blackbeard, Beaufort Inlet, storm effects, settling rate, numerical simulations, scour