

Identifying brumating Northern Diamondback Terrapins (*Malaclemys terrapin terrapin*) by incorporating environmental sensor and drone technology

Michele M. Budd^{1,2}, John Wnek^{1†}, Jim Dugan²

¹Project Terrapin, 195 Marine Academy of Technology & Environmental Science, Cedar Bridge Road, Manahawkin, New Jersey, 08050, USA

²Mordecai Land Trust, P.O. Box 1414, Beach Haven, New Jersey, 08008, USA

Abstract During extended cold water temperatures, the Northern Diamondback Terrapin (*Malaclemys terrapin terrapin*), a brackish water turtle species, undergoes a period of dormancy called brumation. Little is known about brumation, its environmental conditions, or habitats. To establish a range of conditions that a terrapin experiences during brumation, we affixed an environmental sensor to a carapace for one year to record water depth and temperature. Our sensor reading determined that during the brumation period, the terrapin rested in water temperatures < 13.90°C and in a water depth of < 1.0 m. Under similar environmental conditions, we also remotely navigated a drone from a land-based position and found brumating terrapins in a cove within the Barnegat Bay-Little Egg Harbor estuary. The best visibility for terrapin identification occurred when the drone was flown 1.5 – 4.6 m above the water, during a low tide with low tidal heights of less than 0.063 m and low wind speeds of < 12.9 km/h. These findings indicate that drone site surveys can assist researchers in finding locations with brumating terrapins during specific water temperatures and depths.

Keywords terrapin • drone • brumation • environmental sensor • water temperature • water depth

Introduction

The Northern Diamondback Terrapin (*Malaclemys terrapin terrapin*) (Schoepff 1793) is a temperate turtle species that is found along the Atlantic coasts in estuarine systems. (Coker and Ashe 1906; Palmer and Cordes 1988; Brennessel 2006). Terrapins are semi-aquatic and rely on a healthy marsh and a nearby brackish water ecosystem for most of their life cycle for foraging, basking, nesting, and brumation (Burger 1975; Hart and Lee 2006; Tulipani 2013). Juveniles (0 – 3 years) mature while hidden within the high marsh grasses (Burger 1976; Coleman et al. 2014) and forage on small invertebrates within shallow waters (Selman 2018). Most of the adult terrapin activity data along the Atlantic Coast has been collected from coastline population assessments during the nesting season, including mark and recapture studies, trapping, and monitoring surveys (Burger and Montevecchi 1975; Montevecchi and Burger 1975; Brennessel 2006, Selman and Baccigalopi 2012; Budd et al. 2024). Knowledge gaps for this species still remain, especially regarding the locations and activities for the juvenile stages (Lovich et al. 2001) and also the winter brumation locations for adult terrapins (Brennessel 2006).

Brumation is a period of dormancy that is initiated by extended cold water temperatures and allows for the conservation of energy resources by slowing down reptilian metabolism. (Coker and Ashe 1906; Coker 1920; Yearicks et al. 1981; Brennessel 2006). Terrapins begin brumation in early winter depending on water temperature, which can vary latitudinally (Coker and Ashe 1906; Hildebrand 1929; Carr 1952; Brennessel 2006). In northern latitudes, brumation lasts from October until late April (Brennessel 2006). In New Jersey, Yearicks (1981) reported that terrapins will undergo brumation from mid-to-late November until April or May. Farther south, terrapins experience a shorter brumation period, which begins in late October but ends in April in Maryland, March in North Carolina, and in February in Florida (Coker and Ashe 1906; Brennessel 2006).

Terrapins entering brumation will bury themselves into or atop of embankment surfaces and undercuts, or beneath the water (Yearicks et al. 1981). They can be found in clusters or singularly within shallow waters of (1.5 – 2.5 m) (Yearicks et al. 1981), below the lower tidal zone (Brennessel 2006), or in the deep waters of creeks (Hart and Lee 2006), where they burrow into depressions along the floor of the mud substrate

[†]Corresponding author: John Wnek

E-mail: projectterrapin@gmail.com

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(Yearicks et al. 1981; Brennessel 2006). Terrapins will remain inactive until the water temperature warms again (Yearicks et al. 1981) at around 13°C, (Brennessel 2006). Little is known about specific brumation conditions regionally because the terrapins are difficult to detect while they are buried in mud. Their immobility and aggregating during the brumation period makes them vulnerable to poachers (Haramis et al. 2011), or disturbance by dredging (Castro-DeSantos et al. 2019; Dickerson et al. 2004, Brennessel 2006).

The detection and protection of terrapin hibernacula is often challenging and labor intensive, however, because they are either inaccessible or located generally farther from the terrapin's summer home range (Hart and Lee 2006; Castro-Desantos et al. 2019, Lamont et al. 2021). Techniques for capturing terrapins during the brumation period, such as scrape fishing, snorkeling, SCUBA retrieval and cast or dip nets are also tedious, require skill, or are not efficacious (Haramis et al. 2011; Roosenburg and Burke 2018). Consequently, brumation areas are not well known in most terrapin populations across their range.

Unmanned aerial vehicles (UAV) or drones, are used extensively worldwide as a tool for obtaining species behavior and population data (Harden et al. 2009; Elsey 2016). When coupled with artificial intelligence, UAV can now assist in quickly detecting and tracking at-risk species and increase conservation efforts (Gonzalez et al. 2016). In the current study, our purpose was to increase our understanding about terrapin movement and habitat surroundings during brumation by using environmental sensor and drone technologies. We first attempted to establish a range of conditions that terrapins experience during brumation by adhering temperature-depth environmental sensors on female terrapins with a home range within Barnegat Bay, New Jersey, USA. Under similar temperature-depth brumation conditions that were recorded by our sensor, we then determined environmental conditions for identifying brumation habitats by navigating a drone from a land based position to find brumating terrapins in a barrier island's cove within the Barnegat Bay - Little Egg Harbor Estuary (BBay-LEH), New Jersey, USA. By incorporating specific water temperature-depth information from the sensor with the environmental data from drone surveys, we hoped to identify conditions and habitats for terrapin brumation within the estuaries of Barnegat Bay, New Jersey.

Methods

Study Location

Our environmental sensor study took place on an island in Barnegat Bay, New Jersey. The island, which consists primarily

of salt marsh habitat with open bay access (Figure 1) is adjacent to the main channel that leads out to the Barnegat Inlet. The substrate sediment type around the island is primarily sand and its hydrology is due to its proximity to the Barnegat Inlet. Female diamondback terrapins nest on the island from May through July each year. The terrapins nest on a bay beach that they access on the northwest and east sides of the island. The Island also contains a deep-water channel to the east that is used by adult female terrapins for staging during nesting season (Wnek, 2010).

On 9 July 2019, we adhered STAR-ODDI (DST) environmental sensors (21 g dry/13 g in water) using a standard epoxy on eight adult female terrapins that display high nest fidelity and home ranges within Barnegat Bay (Figure 2). The environmental sensors recorded water depth (m, $\pm 0.6\%$ of 0.1 to 100 m) and temperature ($^{\circ}\text{C}$, $\pm 0.1^{\circ}\text{C}$) every 6 hours until recovered on 20 July 2020. Data were downloaded from the sensor using STAR-ODDI DST software and then converted into an Excel file. All data were compared to seasonal values obtained through the National Weather Service (2023) to ensure daily accuracy.

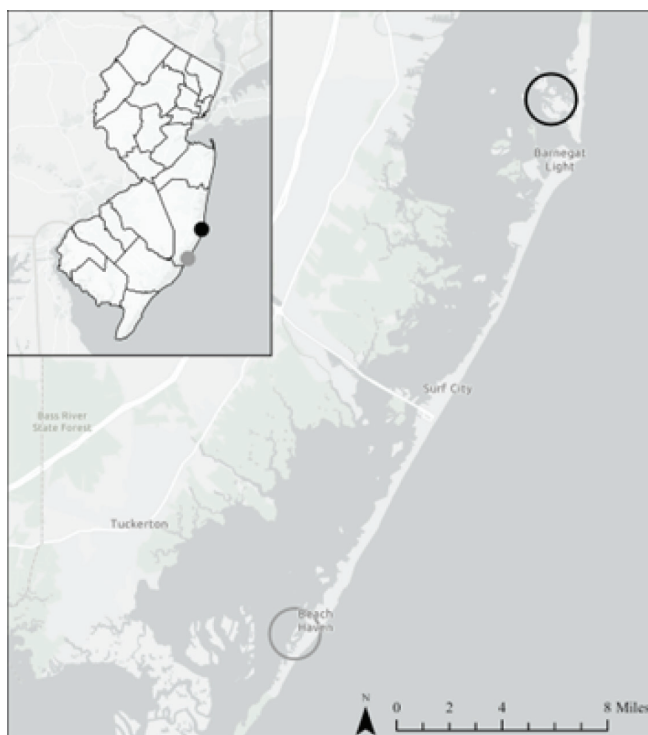


Figure 1. Map of general study areas within Barnegat Bay, New Jersey, USA: Sensor study area (black circle) and drone study area (gray circle). Specific site locations and names were redacted in order to protect the areas of terrapin activity.



Figure 2. Female terrapin fitted with STAR-ODDI (DST) environmental sensor (21 g dry/13 g in water).

Drone Survey

Our drone study was conducted at a barrier island's protective cove within the Barnegat Bay- Little Egg Harbor Estuary (BBay-LEH), New Jersey (Figure 1), located roughly < 30 km from where our sensor study took place. This cove is home to a small population of terrapins that have been monitored by these authors since 2017. The cove is buffered and protected from wind and wave action by the island's interior salt marsh topography and its tidal shoreline characteristics. A slower tidal current enters the mouth of the cove from a thorofare that connects to the open bay. Water salinity for this area is a consistent 29 – 30 ppt (Pang *et al.* 2017). At high tide, the cove's water depth ranges from 1 – 2.1 m from the edge of the embankments to the center of the cove. Terrapin basking is routinely observed within the cove along the tops of the soft, sloping mud embankments, which lead to the cove's mud floor (Figure 4). Nesting occurs from June through July on naturally created sand mounds and also on bay beaches.

We conducted three surveys, using an unmanned aerial surveillance vehicle (UAV/drone), on 5 April, 7 April and 11 April 2023, to determine if brumating terrapins could be identified on the cove's bay floor or within/atop of the embankment surfaces. This time period fits well within our window of brumation that was identified from our environmental sensor study and that guided our drone survey protocol (Figure 3).

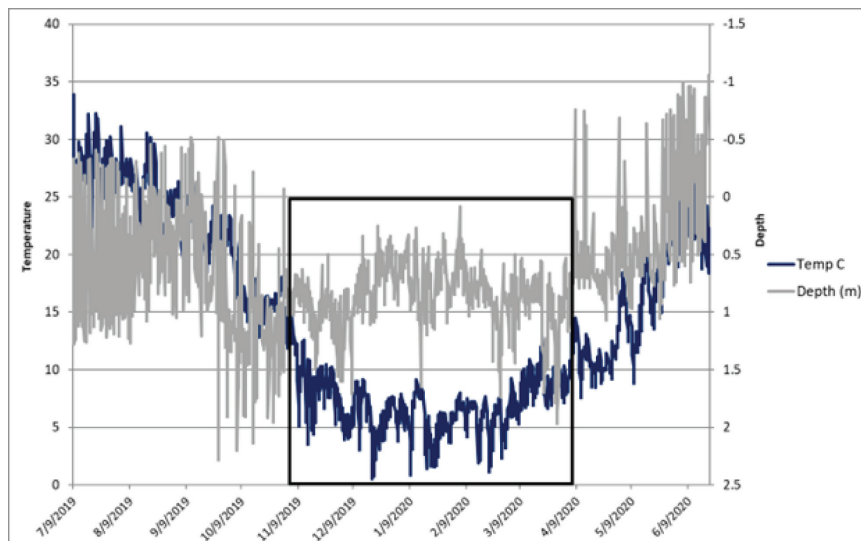


Figure 3. Temperature (°C; darker shade) and depth (m; lighter shade) profile of a mature female diamondback terrapin ("BHIO") that was fitted with DST environmental sensor on 9 July 2019, and recovered on 20 June 2020. The brumation period from early November 2019 to early April 2020 shows no movement above the surface indicating brumation as indicated within the highlighted box.

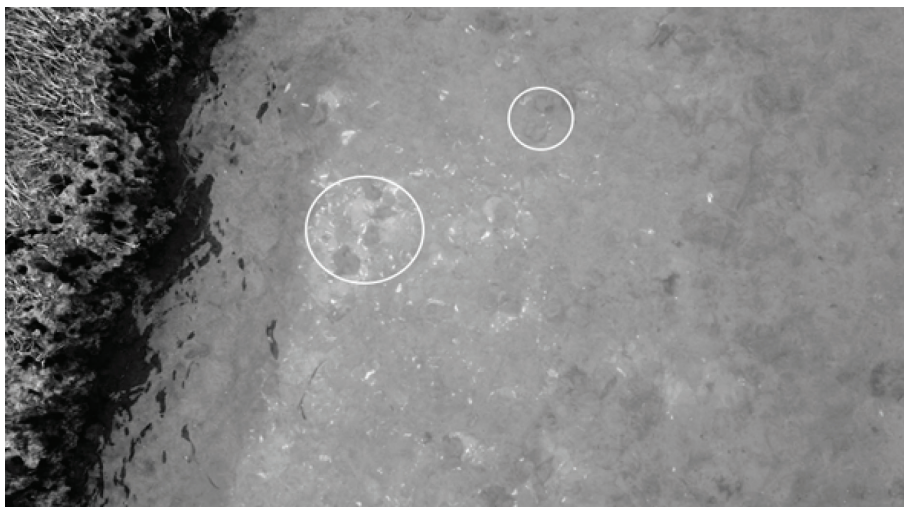


Figure 4. Panned view of brumating terrapins (circled) leading from the sloped shoreline embankments (left) into shallow water on 7 April 2023. This image was taken by using drone technology at 1.5 – 4.6 m above the water and a water depth of < 1 m, and modified to a grayscale for better contrast and definition.

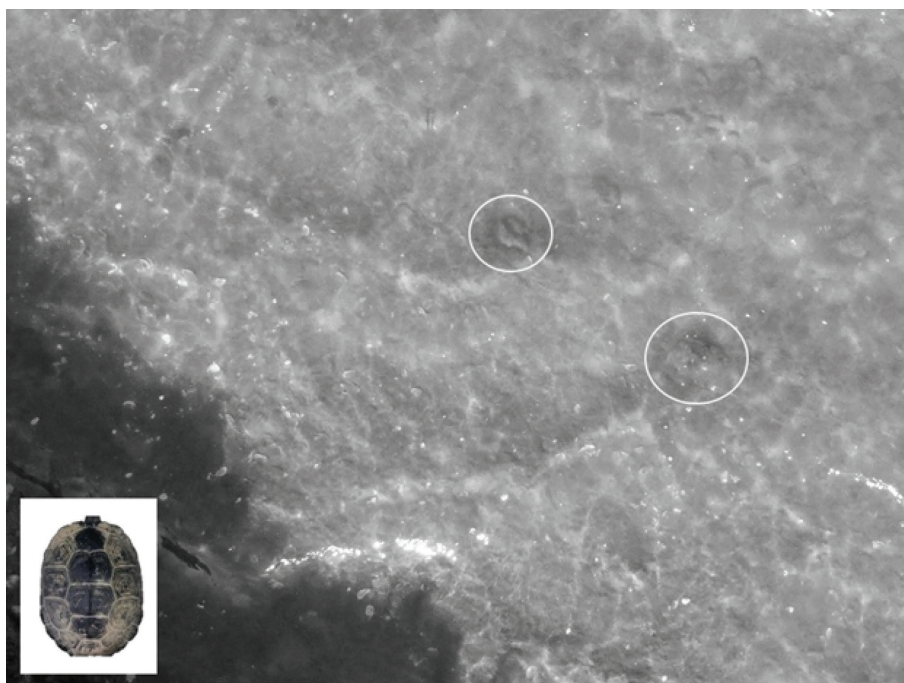


Figure 5. Brumating terrapins found on April 11, 2023 by drone technology at 1.5 - 4.6 m above the water and a water depth of < 1 m (circled). Inset diamondback terrapin image shows the shape and definition of the carapace. This image was modified to a grayscale for better contrast and definition, which reflects similar terrapin mud burrow images by Selman and Baccigalopi (2012).

A visual survey was also conducted by kayak two weeks later on 26 April 2023, to assess the bay floor for inactive or active terrapins. Post-brumation trapping, using baited hoop traps, was conducted from 11 – 18 May 2023, as part of an ongoing mark and recapture project. The hoop traps

were placed on the embankments that were adjacent to the areas where brumating terrapins had been identified to show that the terrapins were still in the same area and that they may be residents of the barrier island's population.

For our drone surveys, we chose monitoring dates and times that occurred during a spring low tide, (tidal heights that ranged from $< 0.01 - 0.06$ m visibility greater than 4.8 km, wind speeds at < 24.14 km/h, and water temperatures $< 13.90^{\circ}\text{C}$). This was a conservative estimate based on the brumation temperatures recorded by our data logger, which showed active brumation temperatures of $< 14^{\circ}\text{C}$ (Figure 3). The bay water temperatures were recorded < 0.16 km from the cove by using a DWELL meter ($^{\circ}\text{C}$, $\pm 0.01^{\circ}\text{C}$), and confirmed by readings posted by USGS (2023a) for Little Egg Inlet, New Jersey. From a land-based position that was located < 0.16 km from the cove, we operated a DJI Mini2 drone with camera and video recording features (ISO Video and Photo Range: 100 – 3200; 4 mm, O ev; f/2.8; effective pixels = 12M $\frac{1}{2}$ 3 CMOS). We flew the drone above the water surface at 1.5 – 4.6 m with video recording and/or observation on the monitoring screen, and scanned the cove's coastline from the edge of the cove's embankments to approximately 6 m toward the cove's center. To account for possible deeper water brumating terrapins, our scanning distance of 6 m from shore was selected based on our data logger's highwater depth readings (Figure 3). We looked for the oval shape of a female terrapin's carapace, and/or the raised darker knobs of the keel along the midline of the carapace as identifying features for brumating terrapins (Figure 5 inset). For mud burrow identification, we relied on descriptions and visuals by Selman and Baccigalopi (2012). When terrapins were observed, the drone was flown to a lower height above the water's surface and screen shot photos were taken.

Results

Environmental Sensor Results

We recovered one of the eight adhered DST from passive integrated transponder (PIT) tagged and notched female terrapin "BHIO", after she nested on a barrier island in Barnegat Bay on 20 June 2020. The temperature data (Figure 3) indicated that the terrapin was exposed to temperatures between a low of 0.57°C on 20 December 2019, and high of 32.25°C on 21 July 2019. In terms of water depth, BHIO was at a maximum depth of 2.28 m of water on 26 September 2019. During brumation, the terrapin showed a more uniform depth pattern from early November 2019 through early April 2020. Water temperature appears to be influenced by water depth. On 19 December 2019, the minimum water temperature (0.57°C) was noted at a water depth of 0.91 m. On 18 January 2020, the water temperature was 4.68°C and the water depth was 0.89 m. The water temperature was 1.40°C at low tide, which shows that water level is influenced by the ocean tidal flow.

Drone Surveys

We found brumating terrapins on the cove's bay floor during all three drone surveys (Table 1, Figures 4 & 5). Thirty-two (32) terrapins were identified following a review of the drone's recorded video footage. Due to an operator error, video footage was only recorded on 7 April and 11 April. We observed terrapins, however, in real time on the drone's monitoring screen during all three surveys. The best visuals were observed on 5 April and 7 April, when the low wind speeds of < 12.9 km/h and cove water depths of < 1.0 m allowed for clear visibility > 4.8 km and footage of the bay floor from the coastline to approximately 6.0 m toward the cove's center. The increased wind speed of 24.1 km/h on 11 April, made it difficult for us to control, stabilize and navigate the drone for longer times at slower speeds and lower heights, while the higher tidal heights and turbidity of the water made it difficult to obtain steady images of the bay floor. The water temperature fluctuated from $11.50 - 13.78^{\circ}\text{C}$ among the survey days, however, brumating terrapins were still found (Figures 4 & 5).

During the drone monitoring, we identified clusters and isolated brumating terrapins on the flat surface of the bay floor, approximately 1.5 m from the edge of the coastline and beyond any embankment grading (Figures 4 & 5), with a mud depth of < 12 cm. We did not see terrapins embedded within the embankment surfaces or toward the center of the cove. We did not observe any terrapins basking, swimming or moving within the water, or in different locations from previous survey observations. These observations were supported through review of the drone video footage.

Post-Brumation Surveys: Kayak, Hoop Traps

No isolated or clustered terrapins were found brumating along the embankment surfaces, on the bay floor, basking, or swimming, when we visually inspected the cove by kayak,

Table 1. Environmental conditions during drone brumation surveys of the cove within Barnegat Bay - Little Egg Harbor Estuary.

	Survey 1 5 April 2023	Survey 2 7 April 2023	Survey 3 11 April 2023
Method	drone	drone	drone
Water Temperature	12.72°C	13.78°C	11.50°C
Water Depth	< 1.0 m	< 1.0 m	< 1.0 m
Tidal Height	0.0067 m	0.007 m	0.063 m
Wind	SE 12.9 km/h	W 12.9 km/h	W 24.1 km/h
Visibility	4.8 km	33.8 km	27.4 km

0 – 6 m from the shoreline, on 26 April 2023, when the water depth was < 1.0 m and with a tidal height of 0.16 m. Extra focus was given to the areas that were 1.5 m from the edge of the coastline and beyond any embankment grading, where brumating terrapins had been seen during the previous drone surveys. Although the water temperature was recorded at 12.70°C during the early morning survey, the water warmed considerably throughout the day to a temperature of 15.20°C.

From 8 –18 May 2023, male and female terrapins were seen basking, swimming and were trapped using baited hoops, in the areas where we had recently identified brumating terrapins during our drone survey. The water temperature for this timeframe was recorded at 16.60– 18.90°C. Any terrapins that we captured were PIT tagged as part of an on-going mark and recapture population study. We recaptured one of these marked terrapins later in the season as she nested 1.8 km from the cove's brumation site.

Discussion

Increasingly, researchers rely more frequently on new and advanced technologies to study and protect at-risk species. Our research allowed for the surveillance of brumating diamondbacks during a vulnerable period and often unknown habitats of their life cycle. By using an unmanned aerial vehicle (drone), we were able to easily, quickly and effectively identify brumating terrapins in a location that showed a high density of terrapin activity during the post-brumation period. This methodology avoids the difficulties that Harden et al. (2007) experienced with transmission and signal strengths of the radio tracking sensors that were used to monitor terrapin movement and habitat temperatures. Our methods are also less labor intensive than conducting visual population head-count surveys (Harden et al. 2009; Levasseur et al. 2019) or randomly probing the bottom of creeks to find brumating terrapins (Yearicks et al. 1981). Knowing the exact location of a terrapin brumation area can be particularly important, especially when estimating the threat and disturbance to a habitat due to restoration or dredging projects. In Massachusetts, Castro-DeSantos et al. (2019) was able to assess associated risks to terrapins from harbor dredging by detecting their movement to and from their summer sub-drainage habitats as they passed through fixed-receiver arrays. Although this process identified harbor dredge zones that were less likely to contain brumating terrapins, the exact brumation locations could not be determined by using this methodology.

We were also able to identify corresponding external conditions of water depth and temperature during brumation

from an environmental sensor that had been affixed to the carapace of an adult female terrapin. We found that the temperatures that were collected by our environmental sensor during brumation aligned with the bay water temperatures for our drone surveys and also support a non-active brumation state when they are compared to the water temperatures for active feeding to occur in other turtle species. Ernst (1976) reported a minimum foraging water temperature of 14°C for spotted turtles (*Clemmys guttata*) in Pennsylvania. However, the average water feeding temperature for males was 18.47°C and 19.93°C for females. A 15°C minimum feeding water temperature was determined by Avery et. al (1993) for juvenile slider turtles (*Trachemys scripta*) in captivity. Future studies should focus on latitudinal variations in the brumation period.

Our environmental sensor temperatures also conform to the minimal water temperature of 13.90°C that we set for our methodology parameters. Our findings are in agreement with water temperatures reported for other brumation studies (Yearicks et al. 1981; Williard and Harden 2011; Akins et al. 2014), as well as the minimal brumation 13.00°C temperature that was cited by Brennessel (2006) for the Massachusetts area. The 13.78°C temperature reading that was recorded during one of our drone surveys was most likely due to slightly warmer temperatures during the previous day, which was then followed by the return of colder temperatures the next day (USGS, 2023a). Since we identified terrapin on the bay floor in the same location as the previous survey, and because the cove's water did not experience an extended warming, this provided us with the evidence that brumation conditions still existed. According to the United States Geological Survey (USGS) for the Little Egg Harbor Inlet (USGS 2023b), there was a shift toward gradually warmer temperatures that began five days after our last drone survey. Water temperatures then ranged from a low of 11.00°C to a high of 17.50°C and with each day's temperatures well above 13.00°C, which may have roused the terrapins from their brumation state.

Our drone monitoring also allowed us to find terrapins nestled in the shallow water (< 1 m) at the bottom of the cove's floor, which was supported by the water depth data that was collected from our environmental sensor. These findings are in agreement with the brumation water depths reported by Yearicks et al. (1981) for creek bottoms at low tide along the Atlantic Ocean side of the Cape May Peninsula, New Jersey (1.5 – 2.5 m), and also Akins et al. (2014) reporting for South Carolina (15 cm) (Table 2). Our brumation mud depths (< 12 cm) conform to the findings of Akins et al. (2014), and Williard and Harden (2011) and also the creek bank brumation burial mud depths reported by Yearicks et al. (1981) (Table 2). In

Table 2. Comparison of environmental conditions for brumation and cold water terrapin studies performed by Yearicks et al. (1981); Williard and Harden (2011); and Akins et al. (2014). All units were converted for comparison purposes.

	This Study	Yearicks et al. (1981)	Akins et al. (2014)	Williard & Harden (2011)
Location	Barnegat Bay- Little Egg Harbor Estuary, New Jersey	Atlantic Coast of Cape May County, New Jersey	South Carolina (by Kiawah Island)	Mansonboro Island, North Carolina
Survey Type	Drone; Environmental sensor	Probing	Temperature data Loggers	Radiotelemetry & visual observation; Temperature data loggers
Water Depth	< 1 m	Creek bottoms at low tide = 1.5 - 2.5 m	0.15 m	Not reported
Mud Depth	< 12 cm	Creek bank sides = 15 - 50 cm; Bank undercuts = <1.0 cm	10 cm	5 - 10 cm (intertidal zone)
Water Temperature	Early April: < 13.90°C	Mid to late November: 6 - 10°C	April: < 18°C	Mean weekly carapace temperature (T _c) during dormancy = 12.4 +/- 1.0°C; Majority of dormancy period at < 20°C
Gender	Male/Female	Male/Female	Male/Female	Female
Location of Brumating Terrapins	Beyond the edges of sloped embankments; underwater burial on cove's bay floor	Underwater burial on bottom of bay floor; atop creek banks and undercuts	Shallow intertidal mud	Burial in mud of intertidal zone

terms of location, we identified brumating terrapins beyond the sloped embankments and buried underwater on the bottom of the cove's bay floor, which is similar to locations reported by Yearicks et al. (1981).

Despite differing regional locations and habitats, we found that similar water temperatures, water depth and burial mud depth exist during terrapin brumation. Our cove site in BBay-LEH provides many of the same ecological elements that are essential for a safe terrapin winter habitat. The uniqueness of this cove, however, is that brumation is occurring in the same area as their other life cycle functions and that a precise location could be determined with drone technology. Based on our environmental sensor's brumation water depth readings and Yearicks et al. (1981) findings that brumating terrapins covered in a thin layer of mud could be easily seen when the water was extremely shallow, we conducted our drone surveys specifically during a low tide with low tidal height, so that optimal viewing could be achieved. Further, we have found that when these brumation and tidal conditions are present, that drone surveys can be effectively conducted to allow for non-invasive viewing of terrapin brumating habitats.

Our environmental sensor data is unique in that it depicts the actual conditions of a brumating adult female diamondback terrapin in Barnegat Bay, New Jersey. Other brumation studies included temperature observations recorded at the onset of brumation, or during periodic field assessments (Yearicks et al., 1981; Hart and Lee 2006; Capella, 2021). Our environmental sensor data recorded temperature and depth four times daily, which indicates that terrapins undergo

fluctuations in temperature consistent with tidal fluctuations and low water events during the winter low tide cycles (Harden et al, 2007). From mid-December 2019 through early February 2020, BHIO experienced a high frequency of water depths lower than 0.5 m than during the first month and last two months of brumation (Figure 3). Terrapins can become active during brumation if water temperatures increase to active temperatures that are over 13°C as reported in Brennessel 2006; however, water temperatures remained below those values throughout a continuous brumation period from November 2019 through early April 2020, with temperatures consistent with the brumation temperatures reported by Yearicks et al. (1981) in New Jersey. BHIO showed activity on 8 April 2020, when the temperature ranged from 12.76°C – 14.52°C, which is consistent with Brennessel (2006) and our terrapin activity at the BBay-LEH cove. During low tides and a strong west wind in the winter, water depths become noticeably lower throughout Barnegat Bay, which is no more than 1.5 m deep on average (Kennish 2001). Therefore, diamondback terrapin brumation areas at Barnegat Bay experience specific conditions for both depth and temperature that are influenced by ocean water influx. Although these conditions align with existing terrapin knowledge, this study utilized this information to identify brumation and post-brumation behaviors in an area of high terrapin densities.

As researchers and lawmakers seek new ways to preserve and restore essential marsh habitats, which are compromised due to global warming and sea level rise, special attention must be directed toward the impact that conservation projects will have on at-risk species. Consequently, new approaches for best management practices at coastal restoration projects

are being designed to protect turtle species, especially for nesting habitats, which reduce take during projects (Evans 2015; Guilfoyles et al. 2019; Clausner et al. 2004). Beach replenishment and dredging operations by the U.S. Army Corps of Engineers, at potential endangered sea turtle locations, include species identification, impact assessment and monitoring of habitats (Dickerson et al. 2004). Changes to dredging equipment, such as turtle tickler chain mats that are dragged along the seafloor, encourage sea turtles to swim away from the project area and potential harm (Clausner et al. 2004; Welp et al. 2024). Biological opinions issued by state and federal agencies are also responsible for enforcing seasonal work restrictions, thus providing further protection, especially during the nesting season (Evans 2019). Although some of these best management practices may have an overlapping benefit for terrapins, few are specifically intended to minimize their risk during brumation (Castro-Santos et al. 2019). For declining diamondback terrapins, it is hoped that drone site surveys will become a standard requirement that is conducted prior to scheduled winter restoration or dredging projects, thereby affording protection to brumating terrapins during this vulnerable period of their lifecycle. This study has contributed to our understanding of movement and environmental conditions that a terrapin experiences, however, further research will help to fill remaining brumation knowledge gaps so that generalizations can be determined about the overwintering process across the range of terrapins in the temperate latitudes.

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