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NC Coastal Highway Vulnerability

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16. Abstract

The vulnerability of North Carolina coastal highways to damage from persistent shoreline erosion and individual storms is a major problem for NCDOT. This report provides an update to a 1991 study that identified "hot spots" where the highway was likely to require some remediation to maintain the transportation link. The present analysis identifies the potential vulnerability for a 20-year period beginning in 2003. The study includes both a long-term analysis based upon the rates of shoreline change and the location of the highway, and a short-term analysis based upon the simulation of individual storms. The latter analysis was only undertaken at an area near Kitty Hawk on the Outer Banks. The overall conclusion of this study is that there are numerous locations along the North Carolina coast where the combination of highway location and shoreline erosion lead to vulnerable conditions now, or within the next 20 years. Current plans are underway for beach nourishment at most of the locations identified as potential hotspots. If these beach nourishment projects are not carried out, then NCDOT will be confronted with many miles of the coastal highway system that will be at risk for damage from persistent shoreline erosion and storms.

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NC Highway Vulnerability Analysis

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Executive Summary

This research investigated the vulnerability of the North Carolina oceanfront highways to damage from long-term shoreline erosion and short-term storm impacts. Working with NCDOT, the PI's have developed a working definition where vulnerability is defined as a loss in integrity and viability of the roadway for anything more than minimal interruption of traffic service due to a moderate storm. In this context, vulnerability implies a loss of pavement and or a breach of the island. This type of damage might take weeks to repair. The deposition of sand on the road (overwash) requiring perhaps a few days to clear is not considered to be a "vulnerable" condition. At the request of NCDOT, a 20-year period is used as the interval to determine vulnerability. From previous studies undertaken by the PIs, this vulnerability has been determined to correlate with the condition of having the distance from the edge of pavement to the shoreline be less than a critical buffer assumed to be equal to 230 ft. When the distance is less than this buffer it has been shown from NCDOT records that the road is likely to be subject to frequent sand burial from overwash, or in the extreme, direct damage to the roadbed. Using this definition of vulnerability, the current study updates a previous (1991) study that identified a number of "hot spots" that have since become areas where NCDOT has had to address possible mitigation alternatives. These alternatives include road relocation, beach nourishment and dune construction.

This analysis of highway vulnerability includes most of the North Carolina coastal highways. The analysis does not include those highways that are located adjacent to shorelines that are part of ongoing U. S. Army Corps of Engineers (USACE) beach nourishment projects: Kure Beach, Wrightsville Beach and Carolina Beach. Also omitted from this study are the oceanfront roads on Bald Head Island and Figure Eight Island as these are private. In addition, the study does not include portions of NC12 on the Outer Banks that are being studied as part of other ongoing NCDOT projects.

The vulnerability analysis begins with an assessment of the long-term shoreline trends and is based upon the long-term annual shoreline change rate combined with the present position of the highway. If the shoreline erodes to a point that the distance between the shoreline and the edge of pavement is less than the 230 ft buffer the highway is said to be vulnerable. The long-term shoreline change rate is determined from an analysis of a shoreline position database spanning approximately 50 years. A linear regression of these shoreline positions is used to determine the current rate of erosion (or in some cases, accretion).

The results of the highway vulnerability analysis based upon the long-term shoreline change are summarized in Table ES-1.

Table ES-1
20-Year Highway Vulnerability

Location	20-Year Highway Vulnerability
Sunset Beach	None expected due to low or no erosion and highway setback from shoreline
Ocean Isle	Potential problems near inlets. Continued USACE dredge spoil from navigation projects will help minimize vulnerability.
Holden Beach	Highly vulnerable unless USACE beach nourishment projects are continued.
Oak Island	Highly vulnerable unless USACE beach nourishment projects are continued.
Bald Head Island	Not studied - private road
Kure Beach	Not studied - long standing USACE beach nourishment
Carolina Beach	Not studied – long standing USACE beach nourishment
Wrightsville Beach	Not studied – long standing USACE beach nourishment
Topsail Island	Highly vulnerable unless beach nourishment (currently under consideration) is implemented.
Bogue Banks	Low vulnerability as long as local and USACE beach nourishment and dredge spoil projects are continued.
Ocracoke Island	Not studied – covered by other NCDOT ongoing studies
Ocracoke Inlet to Oregon Inlet	Not studied – covered by other NCDOT ongoing studies
Kitty Hawk to South Nags Head	Highly vulnerable – focus of ongoing NCDOT mitigation study
Kitty Hawk to Currituck County	None expected due to low erosion rates and large highway setback from shoreline
Currituck County	None expected due to low erosion rates and large highway setback from shoreline

If a section of the highway is considered to be vulnerable a second tool is used to determine the vulnerability of the highway to specific storm events and is referred to as the short-term analysis. The analysis of the short-term impacts of storms included in this study uses a pair of USACE computer models to determine a statistical estimate of the potential for dune erosion from a single storm event and thus takes into account elevation of the highway and the size and elevation of the protective barrier dune. This analysis was applied to a small section of highway in the Kitty Hawk area as an illustrative example. Kitty Hawk was chosen since it is considered to be vulnerable using the 230 ft critical buffer and it is outside of the currently planned nourishment project for the Nags Head area. (In fact, it is the only such section of highway that is considered vulnerable and is outside of a planned nourishment project.) Though vulnerable, the elevation of NC 12 (over 10 ft NGVD) provides significant additional protection. The short-term impacts analysis confirmed what was realized during Hurricane Isabel, that this section of the highway is highly vulnerable to storms with significant storm-surge. Further, the results of this analysis help put into context the damage experienced during Isabel with a representative sample of predicted storm damage from the last 119 years. These results may be most useful when considering the level of protection desired along the oceanfront corridor.

Conclusions and Recommendations

This update of the vulnerability of the North Carolina coastal highways has identified several locations where there are serious current problems as well as additional areas where there are likely to be problems in the next 20 years. Many of the areas where the highway is already within the critical buffer distance of 230 ft from the edge of pavement to the shoreline are already known. For these locations there are current plans in development to deal with the problem. The portions of the coastal highway system that are predicted to become vulnerable are all located in areas where the persistent shoreline erosion has resulted in the initiation of either local or federal planning for beach nourishment. In this regard, while the vulnerability to the highway is not the specific reason beach nourishment is being considered, it is clearly in line to be the indirect beneficiary of nourishment. The implications of this indirect benefit suggest that NCDOT should participate in both project planning, and perhaps project funding. If these beach nourishment projects are not carried out, then NCDOT will be confronted with many miles of the coastal highway system that will be at risk for damage from persistent shoreline erosion and storms.

The short-term analysis provides a mechanism by which one may evaluate the risk of dune erosion for individual events. Using a 119 year hurricane database, including Hurricane Isabel, a stretch of NC 12 in the Kitty Hawk area was studied. This analysis demonstrated the importance of the dune in the overall reduction of risk of highway damage.

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NC Highway Vulnerability Analysis

1. Background

North Carolina has over 200 miles of highways adjacent to an ocean shoreline. The purpose of these coastal highways includes providing access to the beach and the developed areas and to enable evacuation when storms threaten. The proximity of the highways to the ocean means that they are likely to be subject to damage and or loss due to storms and persistent erosion with time. Since the majority of the North Carolina ocean shoreline is eroding, DCM (2003), it is not surprising to find that these shore parallel roads are being lost to the encroaching sea. In addition to long-term erosion, the highway system is exposed to severe storms often resulting in burial with sand during periods of overwash and flooding. In extreme cases the road can be totally lost as storm waves cause excessive erosion. The recent experience of Hurricane Isabel along the Outer Banks is a vivid example of this problem.

Mitigation plans for protecting the highway corridor include a variety of responses. Sand clearing operations may be sufficient when the overwash does not cause structural damage. In some cases it may be necessary to protect the road with beach nourishment and/or dune construction to reduce the impacts of storms and erosion. For more extreme cases it may be necessary to move the road landward. These mitigation alternatives may be used alone or in combination. The North Carolina Department of Transportation (NCDOT) has to be able to anticipate these problems and develop mitigation plans that are timely and effective. The results presented in this report are intended to help with the development of these plans.

In 1991 a study was prepared for NCDOT to assess the potential for the coastal highway system to be damaged as a result of persistent shoreline erosion and/or severe storms, Stone, Overton and Fisher (1991). The results of that study have been successfully applied to identify “hotspots” of erosion that threaten the transportation corridor, the most notable example being the hotspots along NC12 on the Outer Banks. A more recent study focusing on the Buxton area along NC12, Overton and Fisher (2000) presented a vulnerability analysis that combined the long-term erosion with the impacts of short-term storm events. This latter study introduced the use of storm specific modeling to determine the short-term beach and dune changes. This approach has been enhanced with the introduction of a probabilistic method to consider the risk of future storm damage in a study undertaken for URS Corporation for NCDOT along the NC12 hotspots, Overton and Fisher (2003a).

The present report describes the application of these newer methods to determine highway vulnerability to most of the North Carolina coastal highway system. Those portions of NC12 that are being studied as part of other ongoing projects are not included in this project. Other portions of the coastal highway system that are not included in this study are those locations where there are ongoing beach nourishment projects. These long-term U. S. Army Corps of Engineers (USACE) projects have provided protection to the oceanfront highway along these coasts for many years. Therefore the highways along

Kure Beach, Carolina Beach and Wrightsville Beach are not included in the present analysis. Along other portions of the coastal highway system there have been recent USACE or other beach nourishment projects. For these locations a long-term analysis is presented, but no short-term storm impact analysis. The latter has been omitted because the recent nourishment projects have made any discussion of the impacts on dunes irrelevant.

Hurricane Isabel made landfall along the Outer Banks as this project was being completed. The impacts of this storm to both the dunes and highway on the Outer Banks were substantial. Because the short-term storm impact analysis being used in this study is dependent upon a representative profile of the beach and dune, any analysis presented here based upon pre-Isabel profiles could be misleading. Consequently, with the exception of an example analysis at Kitty Hawk, the short-term storm impact of the Outer Banks has been deleted from the present study. The authors are currently working with NCDOT on a new highway vulnerability analysis of the Outer Banks based upon post-Isabel data. The long-term vulnerability analysis based upon the shoreline erosion rates for the Outer Banks is included in the present report.

2. Objective

The objective of this study is to develop assessments of the vulnerability of the NC coastal highway system to the impacts of storms and long-term shoreline erosion. Vulnerability is a subjective term open to varying definitions. Working with NCDOT, the PI's have developed a working definition where vulnerability is defined as a loss in integrity and viability of the roadway for anything more than minimal interruption of traffic service due to a moderate storm. In this context, vulnerability implies a loss of pavement and or a breach of the island. This type of damage might take weeks to repair. The deposition of sand on the road (overwash) requiring perhaps a few days to clear is not considered to be a "vulnerable" condition. At the request of NCDOT, a 20-year period is used as the interval to determine vulnerability.

3. Methodology Overview

There are two principal components of this vulnerability analysis: long-term and short-term. The long-term analysis combines a long-term shoreline erosion rate with a minimum critical distance from the highway to the shoreline. When this distance has been reached the highway is deemed to be vulnerable. This approach is similar to that used in the 1991 study by Stone, Overton and Fisher. The short-term analysis combines a storm specific model of beach and dune erosion with a statistical model to determine the probability of the storm response. A description of this combined methodology is presented in Overton and Fisher (2003a), and some of that material is presented in this report for completeness.

4. Long-term Erosion Rate Analysis

The long-term erosion rate or, more specifically, the average annual long-term erosion rate is a frequently used measure of shoreline change. Shorelines accrete or erode as a consequence of the net balance of sediment moving to or away from the beach. This sediment balance includes the transport of sediment from both the nearshore and the offshore portions of the coast as well as the supply of sediment from other locations along the coast.

The computation of the long-term erosion rate is based upon the change in location of the shoreline as determined from aerial photographs. The shoreline is often defined as the “wet/dry line” that appears on the beach. The North Carolina Division of Coastal Management (DCM) uses this definition in their regulatory processes that deal with erosion rates. The DCM long-term erosion rate is computed from the change in shoreline position over an approximately 50-year period. The authors of this current report did the most recent computation of the DCM erosion rate based upon a 1998 set of aerial photographs and historical National Ocean Survey topographic charts (T-sheets), Overton and Fisher (2003b). The use of the T-sheets is a new addition to the North Carolina program designed to remove some of the difficulties experienced with the older historical aerial photographs. The use of the 1998 photographs and the T-sheets represents an update of the erosion rates from the Stone, Overton and Fisher (1991) report.

The DCM method for determining the erosion rate only uses two shoreline dates. This is referred to as the “end-point” method. When there are sufficient additional sets of aerial photographs for other dates one can compute a rate by taking a linear regression of all of the dates. Two data sets have been combined for this study in order to enable the linear regression analysis. The first is a research database originally compiled by Dr. Robert Dolan at the University of Virginia capturing shoreline changes from 1945 through 1986 and updated by the authors in 1992 with the 1992 shoreline data, Benton, et al., (1993). The 1998 photographs and the T-sheets have been added to the database for the present study so that a linear regression of all of the available shoreline dates could be used to determine the long-term erosion rates.

The previous highway vulnerability studies undertaken by the authors use a minimum distance of 230 ft (defined as the ***critical buffer distance***) between the ocean-side edge of pavement and the shoreline as a standard for when the highway is vulnerable. This distance was first reported in the highway vulnerability analysis undertaken by Stone, Overton and Fisher (1991) and is based upon NCDOT field office records. Once this minimum distance occurs the historical records suggest that NCDOT has usually taken some remedial action. In most cases this remediation is the relocation of the highway.

5. Long-term Erosion Results

The results of this highway vulnerability analysis due to long-term erosion are organized by islands, beginning with the southernmost portion of the North Carolina coast. For each island, one or more graphs illustrate the position of the 2003 shoreline and the predicted position of the shoreline in 20 years (2023). The predicted shoreline position is determined by moving the 2003 shoreline landward or seaward according to the linear rate of shoreline change times 20.

The highway used in this vulnerability analysis is the paved road closest to the ocean shoreline. All distances were measured from the ocean-side edge of pavement (as interpreted from the aerial photographs) to the active shoreline as seen on the most recent aerial photographs (usually 1998). This shoreline is the wet/dry line, similar to, but not exactly the same as the mean high water line. The transects shown on the figures indicate the locations of the profiles used in the short-term portion of the study (as provided by several sources) and in most cases are 1,000 ft apart. Photographs showing transect locations are included for each island as well.

Each of the long-term erosion graphs includes the position of the 230 ft critical buffer distance. One can easily determine from these figures if the edge of pavement was within this buffer in 2003, or if it will be within this buffer by 2023.

5.1 Sunset Beach

Figure 1 shows the transect locations used in the analysis of Sunset Beach. The first transect is located where the improved road begins along the mid-section of the island. The transects are numbered from west to east. Figure 2 shows the distance from the edge of pavement to the 2003 and 2023 shorelines as well as the distance from the edge of pavement to the 230 ft buffer (vulnerability criterion). Most of the improved road is greater than 600 ft from the shoreline, both in 2003 and 20023. In fact, the long-term shoreline change trend on Sunset Beach is accretion. This accretion is reflected in fact that the distance between the active shoreline and the highway is increasing with time. Therefore it is unlikely that there will be any significant highway vulnerability issues on this island in the next 20 years.

5.2 Ocean Isle

Figures 3a and 3b show the transect locations used in the analysis of Ocean Isle Beach. The 28 transects are numbered from east to west for this island. There was a USACE beach nourishment project along the eastern portion of the island in 2001. The approximate location of the beach nourishment was from transect 3 to transect 16. In addition, dredge spoil from recent USACE navigation improvement projects at the adjacent inlets have placed material on the beach on the eastern end of the island. Figure 4 shows the distance from the edge of pavement to the 2003 and 2023 shorelines as well as the distance from the edge of pavement to the 230 ft buffer. Transect 2 at the far eastern end of the island is the only one of concern. This transect is close to Shallotte Inlet. Inlets are areas of significant shoreline change (both erosion and accretion) and are considered high hazard areas by the NC Division of Coastal Management. Highways near inlets are often at risk due to the unstable nature of inlet shorelines. In the case of Ocean Island Beach, it appears that the problem is localized at the inlet, and therefore it probably will not require a major NCDOT initiative to mitigate. Continue USACE projects may be sufficient to protect the road. However, it is possible that the portion of the highway closest to the inlet may be lost at some point in the future. The earlier Stone, Overton and Fisher (1991) report identified a potential problem along the eastern end of Ocean Isle Beach. The current analysis indicates that this problem has been resolved with the USACE beach nourishment and dredge spoil placement activities.

5.3 Holden Beach

Figures 5a and 5b show the locations of the transects used in the analysis of Holden Beach. The transects are numbered from east to west. Figure 6 shows the distance from the edge of pavement to the 2003 and 2023 shorelines as well as the distance from the edge of pavement to the 230 ft buffer. As shown in Figure 6, most of Holden Beach is close to being within the critical buffer and transects 2, 4-6, and 11-12 are within the buffer, i.e., are now, or are expected to be vulnerable by 2023. Shoreline erosion problems are well known on Holden Beach, and the Corps of Engineers has been working with the community and the state to deal with this problem. In 2003 the USACE placed sand along approximately 2 miles of the eastern end of the island (to about transect 12) as part of navigation improvement project (a Section 933 project). This material (and future similar projects) may be sufficient to protect both the homes and the highway on Holden Beach. No additional remediation by NCDOT appears to be warranted at this time. However, Holden Beach will continue to be a place of concern, and NCDOT should encourage (and perhaps participate in) future USACE projects that will add sand to the Holden Beach shoreline.

5.4 Oak Island

Figures 7a-7d show the locations of the transects used in the analysis of Oak Island. The 63 transects are numbered from west to east. Figure 8 shows the distance from the edge of pavement to the 2003 and 2023 shorelines as well as the distance from the edge of pavement to the 230 ft buffer. The distances from the 2003 and 2023 shorelines and the edge of pavement are based upon the 1998 aerial photography that was available for the study. However, in 2000 there was a beach nourishment project undertaken by the USACE as part of a turtle habitat restoration project. Thus, the distances shown in Figure 8 are not an accurate picture of the current or future condition on the island. In addition, Oak Island is included in a large USACE project to place material dredged from the navigation channels for the Port of Wilmington on the nearby beaches. While it would appear from Figure 8 that Oak Island is or will be in the future a problem for NCDOT, this is not likely to be the case if the federal projects are in fact implemented in the future. One should also note that the distances shown on Figure 8 for transects 40 to 43 are where the road that was used in the analysis makes a significant shift away from the oceanfront.

5.5 Bald Head Island

Bald Head Island was not included in this study as there are no public roads on the island.

5.6 Kure Beach

Kure Beach was not included in the study due to the fact that there is a well-established USACE beach nourishment program for the island.

5.7 Carolina Beach

Carolina Beach was not included in the study due to the fact that there is a well-established USACE beach nourishment program for the island.

5.8 Wrightsville Beach

Wrightsville Beach was not included in the study due to the fact that there is a well-established USACE beach nourishment program for the island.

5.9 Figure 8 Island

Figure 8 Island was not included in this study as there are no public roads on the island.

5.10 Topsail Island

Figures 9a – 9h show the locations of the transects used in the analysis of Topsail Island. There are 117 transects, numbered from west to east. Figure 10 shows the distance from the edge of pavement to the 2003 and 2023 shorelines as well as the distance from the edge of pavement to the 230 ft buffer. As seen in Figure 10, most of the coastal highway on Topsail Island is currently within the critical buffer. The shoreline erosion problems on Topsail Island are well documented and there is considerable ongoing interest in a beach nourishment project to rebuild the beach. Each of the three communities on Topsail Island (Topsail Beach, Surf City and North Topsail Beach) is currently investigating the feasibility of beach nourishment, either with the USACE or as a non-federal project. Beach nourishment will of course reduce the vulnerability of the coastal highway on Topsail Island. However, there are likely to be major hurdles (either financial or due to a limited sand supply) that may make it difficult for one or more of these projects to come to fruition. If beach nourishment does not occur in the near future then significant portions of the coastal highway on Topsail Island will be at risk. Since beach nourishment feasibility studies are currently underway, a highway vulnerability risk analysis was not included in the present study. NCDOT should monitor the progress of the beach nourishment planning and consider playing a role in these plans.

5.11 Bogue Banks

Figures 11a – 11h show the locations of the transects used in the analysis of Bogue Banks. There are 129 transects numbered from east to west covering the entire island. Figure 12 shows the distance from the edge of pavement to the 2003 and 2023 shorelines as well as the distance from the edge of pavement to the 230 ft buffer. As seen on Figure 12, most of the ocean highway is just outside of the critical buffer both in 2003 and 2023.

There is a section of highway in the middle portion of the island that is currently inside the critical 230 ft buffer (transects 75-85) as well as a few other isolated transects. The data shown in this figure is based upon the 1998 set of aerial photographs. However, there has been a recent (2002) county sponsored beach nourishment project on Bogue Banks. Since the current analysis is based upon pre-2002 shorelines, the impacts of this 2002 project are not seen in the results. In addition, the USACE is working with the local communities to provide additional sand as part of the Morehead City Harbor dredging project. Consequently, it appears that the threat to the coastal highway due to shoreline erosion has been reduced and that the proposed additional beach restoration projects will further reduce the highway vulnerability in the future.

5.12 Ocracoke Island

Hurricane Isabel occurred in September 2003, while this project was being completed. The impacts of this storm on the Outer Banks were substantial in general, and on NC12 in particular. These impacts have been documented by the authors in a special edition of Shore and Beach, Overton and Fisher (2004). There was considerable damage to NC12 on Ocracoke Island. Much of this damage occurred at the hotspot that had been previously identified in the Stone, Overton and Fisher (1991) report. The problems on Ocracoke Island are therefore well known to NCDOT, and there are several ongoing projects, including a new USACE study aimed at dealing with the protection of NC12 on Ocracoke. An analysis of the vulnerability of NC12 is not included in the present study since it is the focus of these other studies that will use post-Isabel shoreline data,

5.13 The Outer Banks from Ocracoke Inlet to Oregon Inlet

This portion of the Outer Banks is currently being studied as part of a series of contracts between URS-North Carolina and NCDOT. The authors are participating in the highway vulnerability portions of these studies. The shoreline data being made available for these studies is more current than the data being used for most of the shorelines used at the other locations in the present report. In order to avoid overlap and possible confusion, this portion of the Outer Banks is not included in the present study.

5.14 Kitty Hawk to South Nags Head

While Hurricane Isabel damaged portions of the Outer Banks north of Oregon Inlet, it was nonetheless decided to include some of the highway vulnerability analysis for NC12 for this area in the present report. Again, this analysis is based upon the 1998 aerial photography, and therefore should only be taken as a guide as to the potential problems along this portion of the coast. Figures 13a-13f show the location of the transects used in this portion of the study. There are 102 transects numbered from north to south extending from border between Dare and Currituck Counties and South Nags Head. Figure 14 shows the distance from the edge of pavement to the 2003 and 2023 shorelines as well as the distance from the edge of pavement to the 230 ft buffer. The northern portion of this section of NC12 is well known for its current high level of vulnerability from storms. The data shown here confirms this status. NCDOT is currently working on a number of alternatives for dealing with the fact that the edge of the pavement is very close to the shoreline. This section of NC12 is also discussed in the next section of this report dealing with short-term storm impacts.

5.15 Kitty Hawk to Currituck County

Figures 15a-15c show the locations of the transects used in the analysis of the portion of NC12 from Kitty Hawk to the Currituck County line. There are 50 transects numbered from south to north covering the paved portion of the oceanfront highway (NC12). Figure 16 shows the distance from the edge of pavement to the 2003 and 2023 shorelines as well as the distance from the edge of pavement to the 230 ft buffer. Based upon this analysis there is no present or future (up to 2023) vulnerability for this portion of NC12. This low vulnerability is due to the combination of the distance from the shoreline to the edge of pavement as well as the low erosion rates. The latter are evident from the fact that at the scale of Figure 16 there is no discernable difference between the predicted positions for the 2002 and 2023 shorelines.

5.16 Currituck County

Figures 17a-17d show the locations of the transects used in the analysis of the coastal highway in Currituck County. There are 59 transects numbered from south to north covering the paved portion of the oceanfront highway (NC12). Figure 18 shows the distance from the edge of pavement to the 2003 and 2023 shorelines as well as the distance from the edge of pavement to the 230 ft buffer. There are no areas along this stretch of the coast where the highway is vulnerable between today and 2023 based upon the critical buffer criterion. These results are similar to the previous section in Dare County is where the large distance between the highway and the shoreline, as well as the low erosion rates combine to yield a low vulnerability.

6. Highway Vulnerability due to Short-term Storm Impacts at Nags Head

The long-term erosion rates are the result of a combination of several factors that influence shoreline change, including storms, sediment supply and sea level rise. While the impact of storms on shoreline change are included in these rates, the initial impact is smoothed or averaged over the time period of the dataset since the data also include post-storm recovery of the beach. When a storm erodes a beach, significant post-storm accretion of the shoreline position often occurs within a relatively short period of time (days to months) after the large storm waves and the storm tides have receded. However, the storm erosion of the dunes will take longer to recover. Large dunes help to protect the highway from both flooding and direct scour during the storm. Therefore the loss of these dunes from storms increases the vulnerability of the road to future storm damage as well as increased maintenance costs related to the post-storm removal of sand deposited on the road.

The short-term storm impact analysis employed in this study is based upon the SBEACH and EST models developed by the U. S. Army Corps of Engineers. The SBEACH model simulates the changes that occur on the beach and dunes during a single storm, and the EST model develops a statistically based prediction of the impact of a wide range of storms. The approach for considering storm impacts was developed by the authors of the present study in related work on NC12: Overton and Fisher (2000) and Overton and Fisher (2003).

A portion of NC12 in the Nags Head area of the Outer Banks was selected to demonstrate this approach to modeling highway vulnerability due to storms. Kitty Hawk was chosen since it is considered to be vulnerable using the 230 ft critical buffer and it is outside of the currently planned nourishment project for the Nags Head area. In addition, this area was selected because NCDOT has for some time been dealing with options to protect the highway at this location and because of the damage done by Hurricane Isabel in September 2003. The study area is approximately a mile in length from the Kitty Hawk pier south (Transects 2 and 8, Figure 13a). These seven transects were selected for this analysis, NH2-NH8, and are spaced 1000 ft apart.

The objective of this short-term storm impact analysis was to one, determine the loss of dune as a function of return period, two determine the return period associated with 50% loss of the existing dune (Overton and Fisher, 2003b), three determine the relative significance of Hurricane Isabel in the context of previous storms along the Outer Banks and four determine the risk associated with damage comparable to Hurricane Isabel occurring in the next 20 years.

6.1 SBEACH Model

SBEACH (Storm-Induced Beach Change) is one of a handful of models that are currently being used by coastal engineers to determine shoreline changes due to storms. The data input into the SBEACH model include a description of the storm, the beach and nearshore geometry and the characteristics of the sediment. The storm data includes time-varying details of the waves, tide and surge. The Overton and Fisher (2002) Report included both tropical and extratropical storms in the SBEACH analysis. For the present study only tropical storms are considered. Since the SBEACH and EST analysis are only being used to model the dune changes, and since the extratropical storms do not have any significant impacts on the storm, these storms are not included in the present study.

SBEACH is a two-dimensional model. This means that the topography for each site studied, extending from the landward point of interest, across the beach, and through the nearshore to a location offshore where minimal sediment transport by the storm waves will occur, must be input into the model

The final set of input is a description of the sediment. In particular, the SBEACH model needs the sand particle diameter characteristic of the entire profile including the nearshore, the beach and the dunes. These data are generally determined from field samples that are analyzed using standard soil size analysis testing procedures.

6.2 Hurricane Storm Data

Storm data needed for the SBEACH model include the time history of the change in sea level (surge hydrograph) and the time history of the wave height and wave period (wave hydrographs). The USACE has published the results of a comprehensive study of hurricane storm surge along the Atlantic and Gulf coast (Scheffner, et al., 1994). This study used the Advanced Three-Dimensional Circulation (ADCIRC) model to compute storm surge from the hurricane wind and storm path data. The ADCIRC model is a well-accepted method for simulating hurricane surge.

The Scheffner report indicates that 16 hurricanes had storm surges (not including the regular astronomical tide) of 1 ft or greater between 1899 and 1985 at this offshore location. Hurricane Gloria (1989) is included in this database. A comparison of the recorded storm surge at the FRF (less than 5 ft) and the ADCIRC predicted surge (over 10 ft) for Hurricane Gloria suggested that there is a potential problem with the ADCIRC results for this storm. Since the very large predicted surge would skew the EST results in this present analysis, Hurricane Gloria was deleted from the database. By dropping Gloria, and adding Isabel, a total of 16 storms were included in the revised storm database.

The Scheffner report only presents the peak storm surge for each of the hurricanes studied. Since the SBEACH model requires both the surge hydrograph and the wave hydrograph, additional information is needed. Dr. Scheffner was contacted, and he subsequently made available the computer results for the ADCIRC analysis including the storm hydrographs. These hydrographs are the simulated time histories of the surge.

In addition to the surge hydrograph, the SBEACH model requires the wave height and wave period hydrograph. These data were not available (with the exception of Hurricanes Isabel) and therefore they were estimated after a review of wave records from the offshore data buoys and the U.S. Army Corps of Engineers Field Research Facility research pier (FRF) at Duck, NC. A simple equation to distribute the wave heights over time was adopted using a sine (squared) function with the maximum hurricane wave height set at 30 ft (when the water depth is 60 ft) for all of the storms and the maximum wave period set at 15 sec. It should be noted that the SBEACH model shoals the waves as they approach the shore, and therefore the period and the bathymetry determine the actual waves on the beach. The details of the wave and surge hydrograph simulations are presented in Overton and Fisher (2002). In the analysis, each of the storms in the HURDAT database was modeled for a spring tide condition, with the peak surge occurring at high, mean and low tide. Thus, for each storm (except Isabel), there were three SBEACH runs.

6.3 Cross-shore Profiles

The cross-shore profiles for all seven transects used in this analysis are shown in Figure 19. These data are from a December, 2001 USACE, Wilmington District, survey. This survey is part of the data collected by the Corps for a beach nourishment feasibility study currently under consideration. In Figure 19 the profiles have been shifted such that the zero on the horizontal axis is located where the mean high water line (MHW) intercepts the profile. From this figure one can see that beyond the offshore bar the profiles are all very similar. Figure 20 shows the details of the profiles in the area of the dunes. In this case the profiles have been shifted such that the zero on the horizontal axis is located at the 6.7 ft contour (relative to National Geodetic Vertical Datum, NGVD). This latter elevation is the height of the maximum surge for Hurricane Isabel. By using this as the common elevation for the shift in the horizontal axis one can more readily see how the geometry of the seven dunes differ with regard to the impacts of wave runup and overwash. Of particular note on Figure 20 are the dune profiles for NH5 and NH6 (both in bold). These two dune profiles are considerably larger, either by total volume or by maximum crest elevation than the other five dune profiles. The SBEACH simulation of Hurricane Isabel results in all but NH5 and NH6 being overtopped. It is also interesting to note the relative low elevation of the dune profile for NH8. At this location the maximum dune crest elevation is about 12 ft, as compared to elevations of over 20 ft for NH6, and almost 18 ft for NH5. In fact, even at the –200 ft distance the elevations for NH5 and NH6 are higher than NH8 at the same relative horizontal position.

Transect NH7 was selected to illustrate the details of the SBEACH analysis. The location of this transect is shown in Figure 13a. Figure 21 shows the cross-shore profile for this transect from the centerline of the highway out to the 30 ft depth contour. There is a well-defined offshore bar and a well-defined dune with a maximum crest elevation of about 18 ft.

6.4 Sediment Data

Two parameters are required by the SBEACH model to characterize sediment, the sediment grain size and the avalanche angle. Sediment data for this area had been previously collected by NCDOT for a related study. The sample collection points were the top of the dune, the toe of the dune, the middle of the beach and the water’s edge. The NCDOT Soils Laboratory analyzed the samples using standard sieves and plotted the cumulative probabilities and mean sediment size determined for each of the collection points. Even though the SBEACH model uses a sediment size that is intended to be characteristic of the entire profile (both above and below the water) this shoreline erosion analysis uses a sediment size based solely on a composite of the samples that were collected above the water. The avalanche angle used in the SBEACH model was 30 degrees, as determined from model calibration with data from Hurricane Dennis reported in Overton and Fisher (2000).

6.5 SBEACH Results for NH7 for Hurricane Isabel

The SBEACH modeling results for Hurricane Isabel for transect NH7 are shown in Figure 22. The model predicts that the dune is destroyed, with sand transported landward across the highway. This is in fact what is understood to have happen at this location during this storm. Both the pre- and post-storm profiles are shown on this figure. The SBEACH results suggest that there was virtually no change along the profile from the toe of the dune seaward. The results show that the dune was overtopped by the combination of the storm waves and surge and this resulted in the erosion of the dune. As shown in the figure, the model transports the dune sand across the profile and deposits it behind the former dune position in a manner similar to the washover fan often found along NC12 after severe storms.

7. Statistical Analysis of Storm Impacts

The SBEACH model estimates the erosion from a single storm. Sixteen hurricanes that have impacted the Nags Head study area were selected to provide a range of historical storm event data in order to place Hurricane Isabel in context by the use of the return period. This statistical analysis was performed by the use of the EST model.

7.1 EST Model

A description of the EST model is included in Overton and Fisher (2002). The EST model input parameters include the tide condition (for the hurricane data), maximum surge, maximum wave height and period and storm duration. The EST model also requires a single response parameter, which for this study is the volume of dune erosion generated from the SBEACH model. The dune erosion is defined as the volume per unit width of beach of dune eroded between the toe of the dune on the ocean side, and the heel of the dune on the landward side. Each simulation is repeated 100 times in order to generate the desired statistics.

7.2 EST Results for Transects NH2-NH8

Table 1 summarizes the vulnerability indicators for all seven transects with regard to the storm dune impact. EOP to MHW is the distance from the ocean-side edge of pavement to the intersection with the mean high water elevation. With the exception of NH2, all transects are vulnerable using the 230 critical buffer. The next column presents the elevation of the road measured at the edge of pavement. The relatively low elevation of NH8 is clearly evident in this table. The last two columns, dune crest (ft) and dune volume (cu ft/ft) are two of the important criteria indicating dune vulnerability. Dune volume is a subjective calculation depending on the designation of the dune toe and dune heel using the pre-storm profile survey data. In general, the location of the toe and heel are determined using the magnitude of the slope of the profile and the breaks in the slope as indicators.

It is useful to consider the high degree of variation in the dune configuration in the along-shore direction to fully understand the vulnerability of the highway. Using volume as criteria, the dunes would be ranked (largest to smallest) as NH5, NH6, NH7, NH2, NH3, NH4 and NH8. The difference between the largest and smallest dune volume is 251 cu ft/ft or approximately a ratio of 5:1. In addition, using dune crest height as a criterion, the dunes would be ranked (largest to smallest) as NH6, NH5, NH7, NH2, NH3, NH4, and NH8. A difference of 8 ft of elevation is noted between the largest and smallest dune crest, a significant range potentially allowing overwash of the smaller dunes and lateral erosion of the neighboring sections. The large range of spatial variation in the dune field suggests that a large range of response in the EST results is expected.

Table 1.
Vulnerability Indicators for NC12.

Profile name	EOP to MHW, ft	Elevation of the EOP, ft	Dune crest, ft	Initial Dune Volume cu ft/ft
NH2	250	10.95	16.0	231
NH3	231	11.47	15.4	59
NH4	188	11.17	15.3	81
NH5	172	12.95	17.5	310
NH6	173	12.54	20.3	182
NH7	167	11.19	17.1	258
NH8	180	9.83	12.3	98

The multiple simulations performed in the EST analysis allow one to create a return period curve where dune erosion is the predicted response. Figures 23a-23g show the EST results for the Nags Head transects NH2-NH8 in the form of loss of dune as a function of return period. Each figure shows both the mean (the solid curve) and plus and minus one standard deviation from the mean. Table 2 summarizes key values from these figures. Consider Figure 23a and Table 2 as an example. The pre-storm profile at NH2 had a dune with an estimated volume of 231 cu ft /ft of beach. The return period for 50% loss of that dune (115.5 cu ft/ft) is approximately 28 yrs (or 20 to 38 yrs using the +/- one standard deviation). This can be restated as, on average, once every 28 years a storm will cause approximately 115 cu ft/ft of dune erosion at transect NH2. If we consider the risk associated with an erosion event that would cause 50% loss of dune in the next 20 yrs, this return period converts to 52% probability of occurrence.

The 100-year response for NH2 is approximately 200 cu ft/ft. It is important to note that this is not the same as the expected erosion for a "100-year storm". When using the "100-year" designation it is necessary to recognize which specific parameter is being used to classify the return period. For example, the 100-year storm based upon maximum storm surge will be different than the 100-year storm based upon the maximum wave height or storm duration, or wave period. In the present analysis the volume of sand eroded from the dune is the parameter being used to determine the return period.

Table 2.
EST results for Kitty Hawk Profiles.

Profile name	Initial Dune Volume, cu ft/ft	Return Period for 50% loss	Risk of 50% loss of dune in a 20 yr period
NH2	231	28	51%
NH3	59	24	57%
NH4	81	30	49%
NH5	310	75	24%
NH6	182	32	47%
NH7	258	42	38%
NH8	98	15	75%

Following the analysis of the dune characteristics, the return period associated with 50% loss of the dune was ranked in descending order, or NH5, NH7, NH6, NH4, NH2, NH3, and NH8. As expected, the dunes with the most robust characteristics have the larger return periods. This is consistent with the expectation that the larger storms are required to erode the larger dunes and larger storms occur less frequently. Finally, evaluating risk indicates that NH2, NH3, NH4 and NH8 (the smallest dunes) have the highest risk of failure (approximately 50% or more). This variation in spatial integrity of the dune system (in the along-shore direction) suggests that the protection provided by the larger dunes (NH5, NH6 and NH7) is diminished by the potential breaching of dunes on adjacent sides and lateral erosion of the dune ridge.

These results could be used to determine the how much risk we are willing to tolerate with respect to potential damage to a transportation corridor. At this Kitty Hawk location two key features render NC12 vulnerable, one, distance to the active shoreline and two, the volume, height and integrity of the protective dune system. It is possible in some locations to mitigate highway vulnerability by dune reconstruction and maintenance, however; at this location, design considerations would likely suggest that beach nourishment (increased distance from highway to active shoreline) is required.

Hurricane Isabel hit the NC coast on September 18, 2004 significantly damaging sections of NC 12 including the Kitty Hawk area. A review of the characteristics of the NC 12 hotspots and the damage caused by Isabel to NC 12 is presented in Overton and Fisher, 2004. It is instructive to examine what happened at Kitty Hawk relative to the results presented above. In order to due this, it is necessary to extract the predicted volume lost due to Isabel using SBEACH analysis and the associated return periods and probability of occurrence in a 20-year period. (Note: Post-storm profiles were not available for this exercise.) These data are noted on Figures 23a-23g and tabulated in Table 3 below.

Table 3.
Interpreting Hurricane Isabel using EST results for Kitty Hawk Profiles.

Profile name	Initial Dune Volume, cu ft/ft	% Eroded due to Isabel	Return Period for loss during Isabel	Risk of Damage Comparable to Isabel in 20 yrs
NH2	231	78	64	27%
NH3	59	100	63	27%
NH4	81	98	86	21%
NH5	310	17	25	56%
NH6	182	26	22	61%
NH7	258	91	86	21%
NH8	98	100	35	44%

(NH5, NH6 and NH7 are highlighted as the most robust dunes in this study area.)

Dune response due to Hurricane Isabel falls into two categories, one, dunes that lost more the 78% (NH2, NH3, NH4, NH7, and NH8) and two, dunes that lost less than 30% of the initial volume (NH5 and NH6). In addition, two of the largest dunes, NH5 and NH6, had the two smallest return periods, suggesting that the damage due to Hurricane Isabel at these dunes is equivalent to a 20-25 yr storm. NH6, however, a dune with a large volume but the third highest crest height, lost 91% of the dune during the Isabel simulation. This only makes sense in the context of considering whether or not the dune is overwashed during the storm. Findings, using either SBEACH results or post-storm field inspections, indicate that overwash causes catastrophic damage to the dune. The conditions that create overwash, while dependent on storm surge and wave height, are highly sensitive to the geometry of the beach and dune. Wave runup and storm setup are not uniform in the along-shore direction. If the maximum crest of the dune at the time of maximum runup and storm surge is not greater than the water level, overtopping and catastrophic loss of the dune will occur. In these SBEACH simulations, Isabel did not overtop NH5 and NH6 and did only minor damage to the base of the dune, no more than simulations of much smaller storms (as ranked by storm surge). NH7, though larger in volume than NH6 yet approximately 0.5 ft lower in elevation, was overtopped and nearly destroyed (91%). This level of detail is storm specific and cannot be illustrated with the EST results presented in Table 2. Only an examination of the particular dune response to the storms in the storm data set reveals the sensitivity to overwash. While eight of forty-six storms caused overwash in the SBEACH simulations for NH6 and NH7, those eight included Hurricane Isabel for NH7 yet did not include Isabel for NH6. Dunes along transects NH2, NH3, NH4, and NH8, the dunes with the lower crests and volumes, were overwashed by approximately 50% of the storms in the storm dataset resulting in nearly complete removal of the dune.

Finally, we can convert return period to risk of occurrence using Hurricane Isabel as our design storm. These results are also in Table 3. We see that there is less than 50% chance of a storm occurring that would do the equivalent damage that Hurricane Isabel did at transects NH2, NH3, NH4, Nh7 and NH8 (e.g., destroy the dune) and there is a greater than 50% that a storm will occur that will do the modest damage sustained at NH5 and NH6.

The results at NH5 and NH6 (lack of failure) are also somewhat contradictory to post-storm reports of damage along NC12 at Kitty Hawk (significant overwash and loss of dunes). Figures 24a and 24b, and 25a and 25b show pre and post-Isabel aerial photographs in the location of transects NH5 and NH6. These photos help to show the limitations of using a two-dimensional model (SBEACH) to analyze a very complex three-dimensional problem. As discussed previously, the SBEACH analysis at these two transects predicts that there is minimal dune erosion at these two transects. From the post-storm photographs it is clear that there was considerable overwash on NC12 in the vicinity of these two transects. The pre-storm photograph show that there are dune crosswalks as well as extensive lot development (implying reduction in dune volume) near both of these transects. Thus, while the SBEACH results predict minimal dune erosion, in fact there appears to have been extensive sand transported across the highway. This contradiction is explained by the inability of the SBEACH model to deal with the dune erosion that probably occurred laterally as the adjacent low portions of the dunes were eroded and overwashed.

8. Findings and Conclusions

This update of the vulnerability of the North Carolina coastal highways has identified several locations where there are serious current problems as well as additional areas where there are likely to be problems in the next 20 years. Many of the areas where the highway is already within the critical buffer distance of 230 ft from the edge of pavement to the shoreline are already known. For these locations there are current plans in development to deal with the problem. The portions of the coastal highway system that are predicted to become vulnerable are all located in areas where the persistent shoreline erosion has resulted in the initiation of either local or federal planning for beach nourishment. In this regard, while the vulnerability to the highway is not the specific reason beach nourishment is being considered, it is clearly in line to be the indirect beneficiary of nourishment. The implications of this indirect benefit suggest that NCDOT should participate in both project planning, and perhaps project funding. If these beach nourishment projects are not carried out, then NCDOT will be confronted with many miles of the coastal highway system that will be at risk for damage from persistent shoreline erosion and storms.

The short-term analysis provides a mechanism by which one may evaluate the risk of dune erosion for individual events. Using a 119 year hurricane database, including Hurricane Isabel, a stretch of NC 12 in the Kitty Hawk area was studied. This analysis demonstrated the importance of the dune in the overall reduction of risk of highway damage. Finally, these results could provide guidance on dune repair and maintenance.

9. Recommendations

This report identifies the portions of the North Carolina coastal highway system that are likely to be vulnerable for the next 20 years. NCDOT should consider developing a mitigation strategy that will minimize the disruption to the transportation system as a consequence of this exposure to severe storms and persistent shoreline erosion. This strategy should include a comprehensive monitoring program as well as active participation in beach nourishment planning where appropriate. The NC General Assembly has charged the NC Division of Coastal Management (DCM) with the responsibility to develop a state-wide shoreline management strategy. NCDOT should consider forming a partnership with DCM to work together on this project. It is clear that the future of the state's coastal highways is going to be intertwined with the management of the shorelines. The degree that NCDOT can work with other state and federal agencies to reduced the vulnerability at the identified hotspots will ultimately determined both the options and the costs for protecting these roadways.

10. Implementation and Technology Transfer Plan

There are several ways to facilitate the transfer of the conclusions and recommendations from this study to others. The authors plan to incorporate the data and analytical techniques into papers for submittal to a technical journal.

It would be useful to hold a technical meeting at NCDOT where the PI's could present the results to the appropriate engineers and managers who have the responsibility to deal with the ever-present problems related to the coastal highway system. These individuals could possibly include the Division Engineers, State Hydraulics Engineer and the Deputy Secretary for Environment, Planning and Local Government Affairs and the State Highway Administrator.

Since the report provides detailed information regarding specific locations along the entire NC coast, it would be useful to provide copies of this report to each of the relevant Division Offices.

11. Cited References

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12. Figures

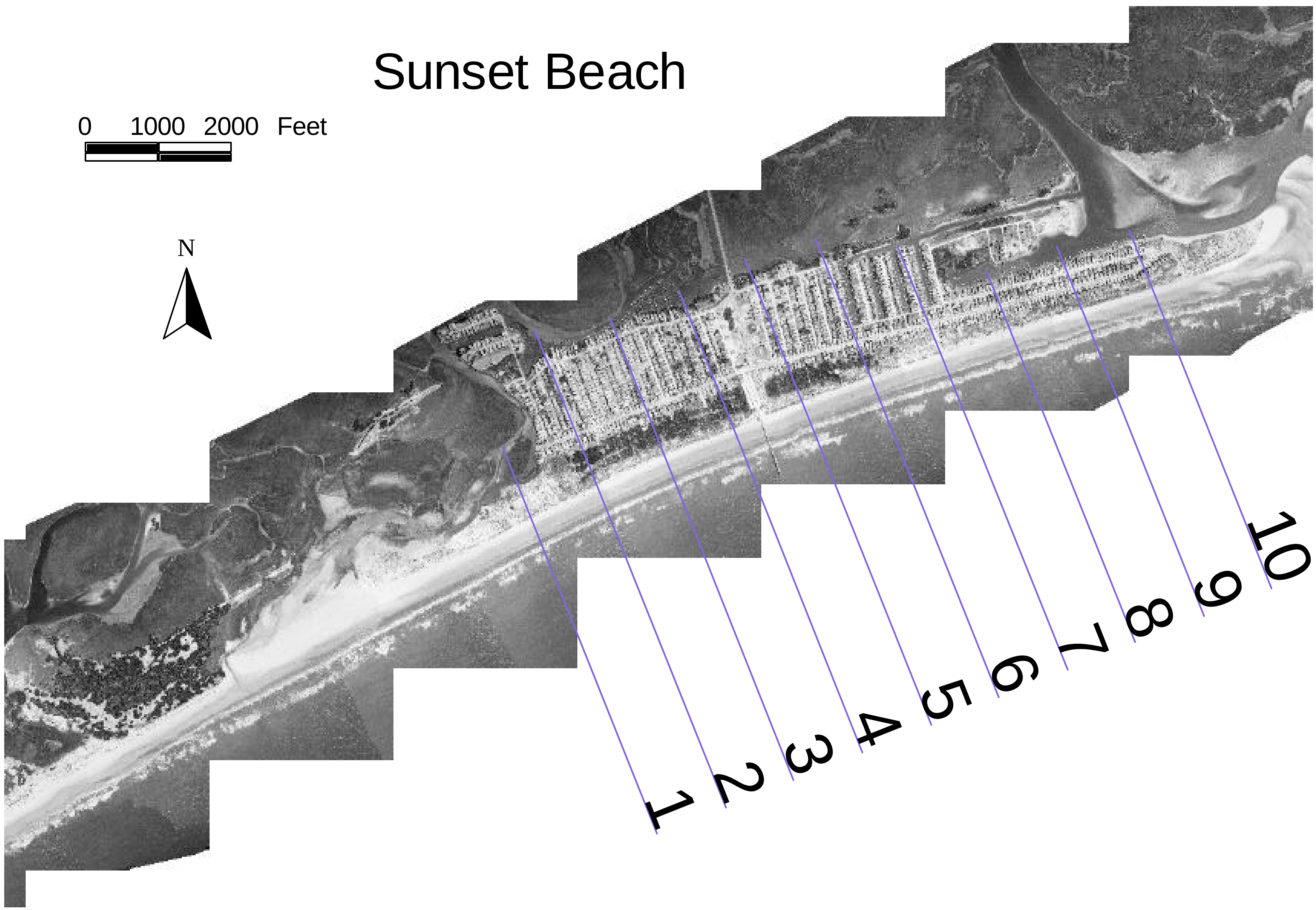

Figure 1. Transect locations on Sunset Beach.

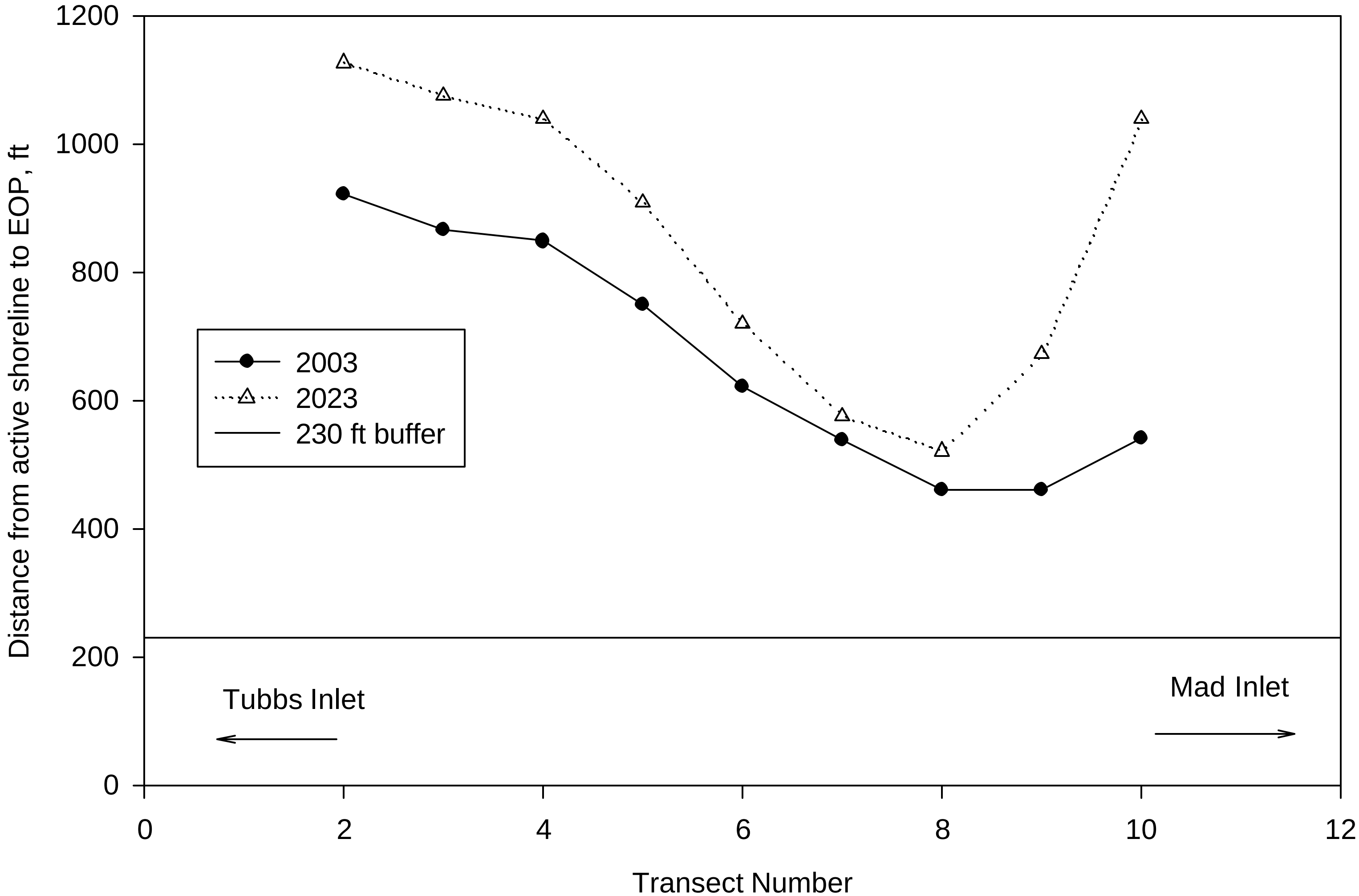

Figure 2. Distance from edge of pavement (EOP) to the active shoreline on Sunset Beach.

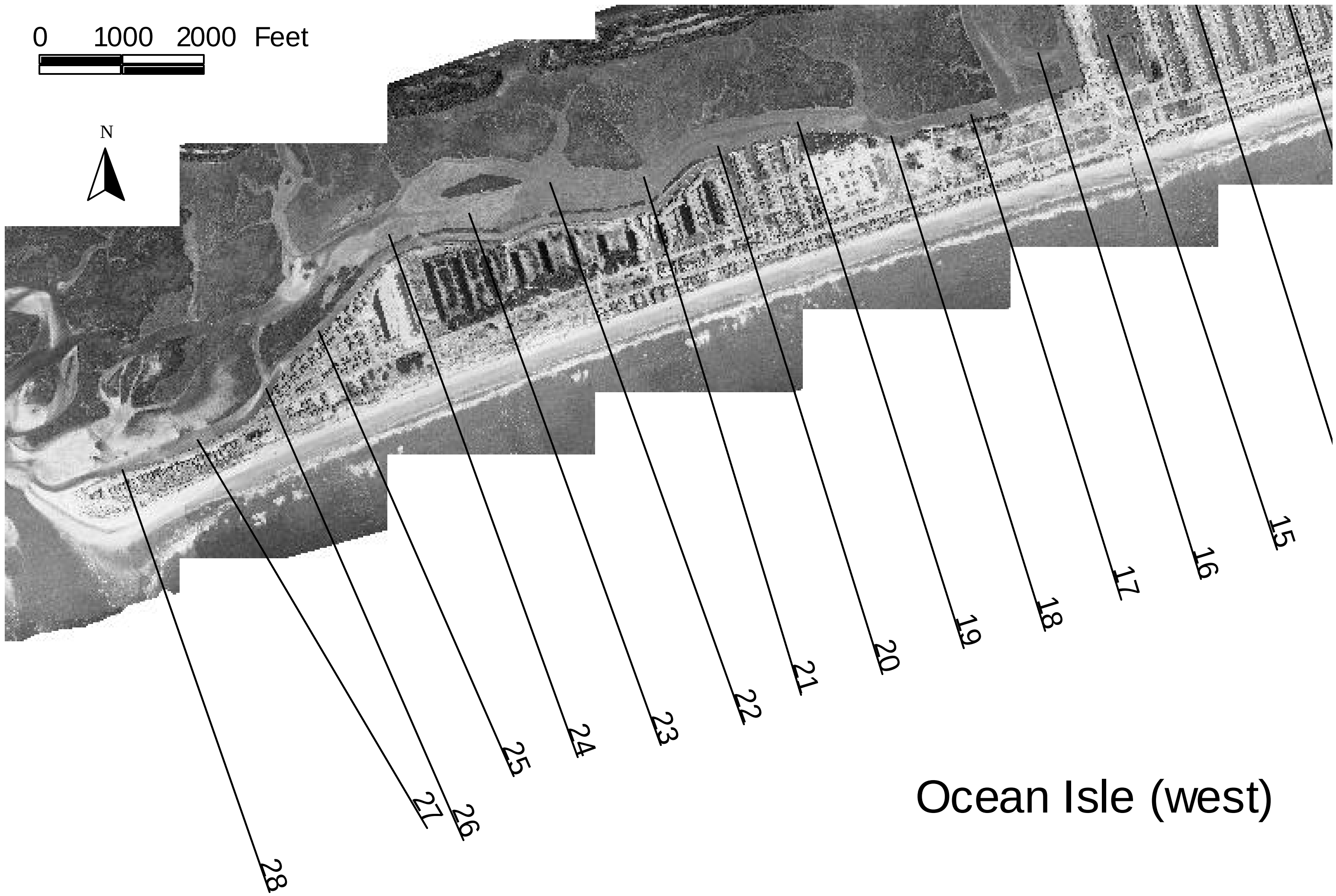

Figure 3a. Transect locations on Ocean Isle.

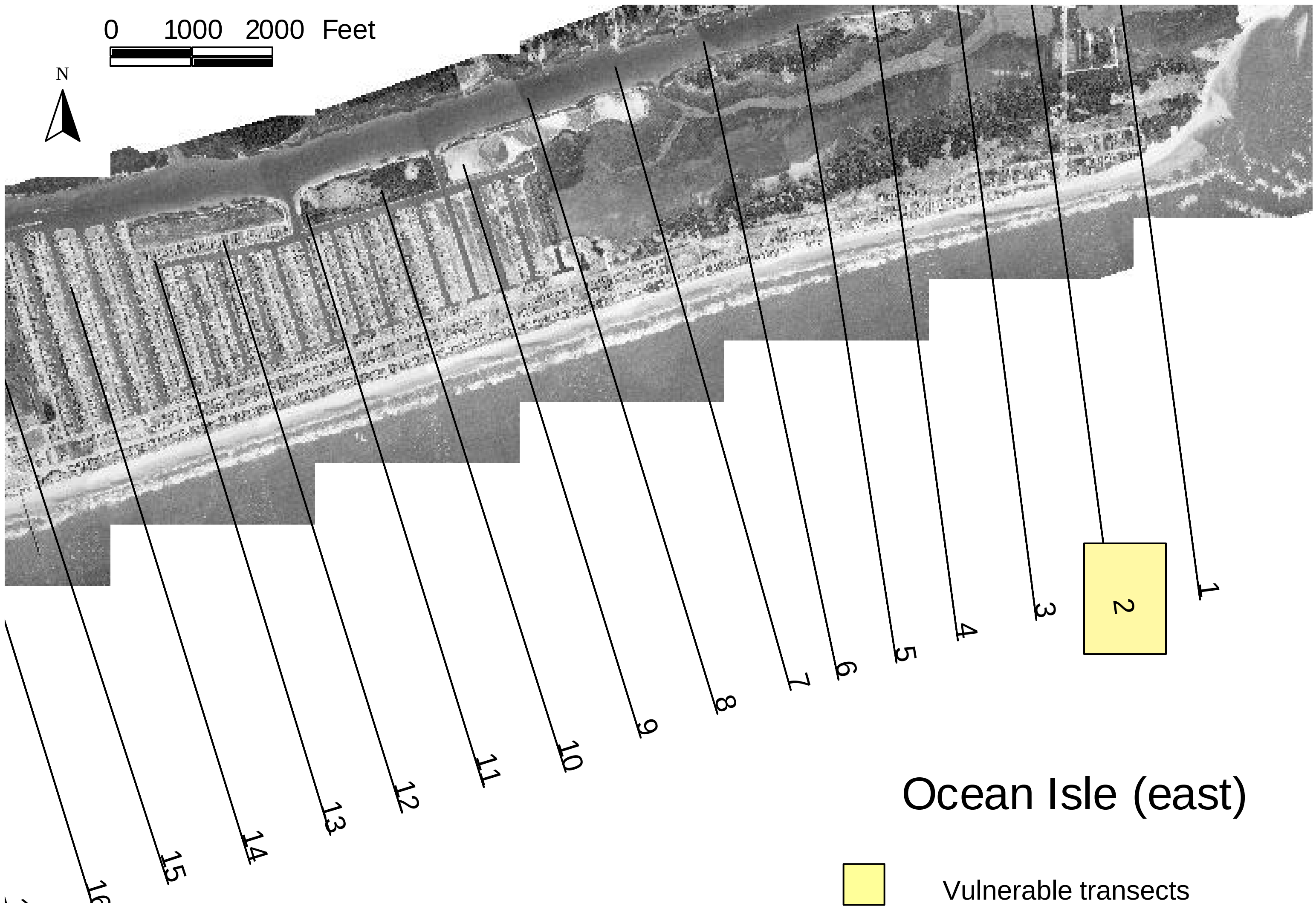

Figure 3b. Transect locations on Ocean Isle.

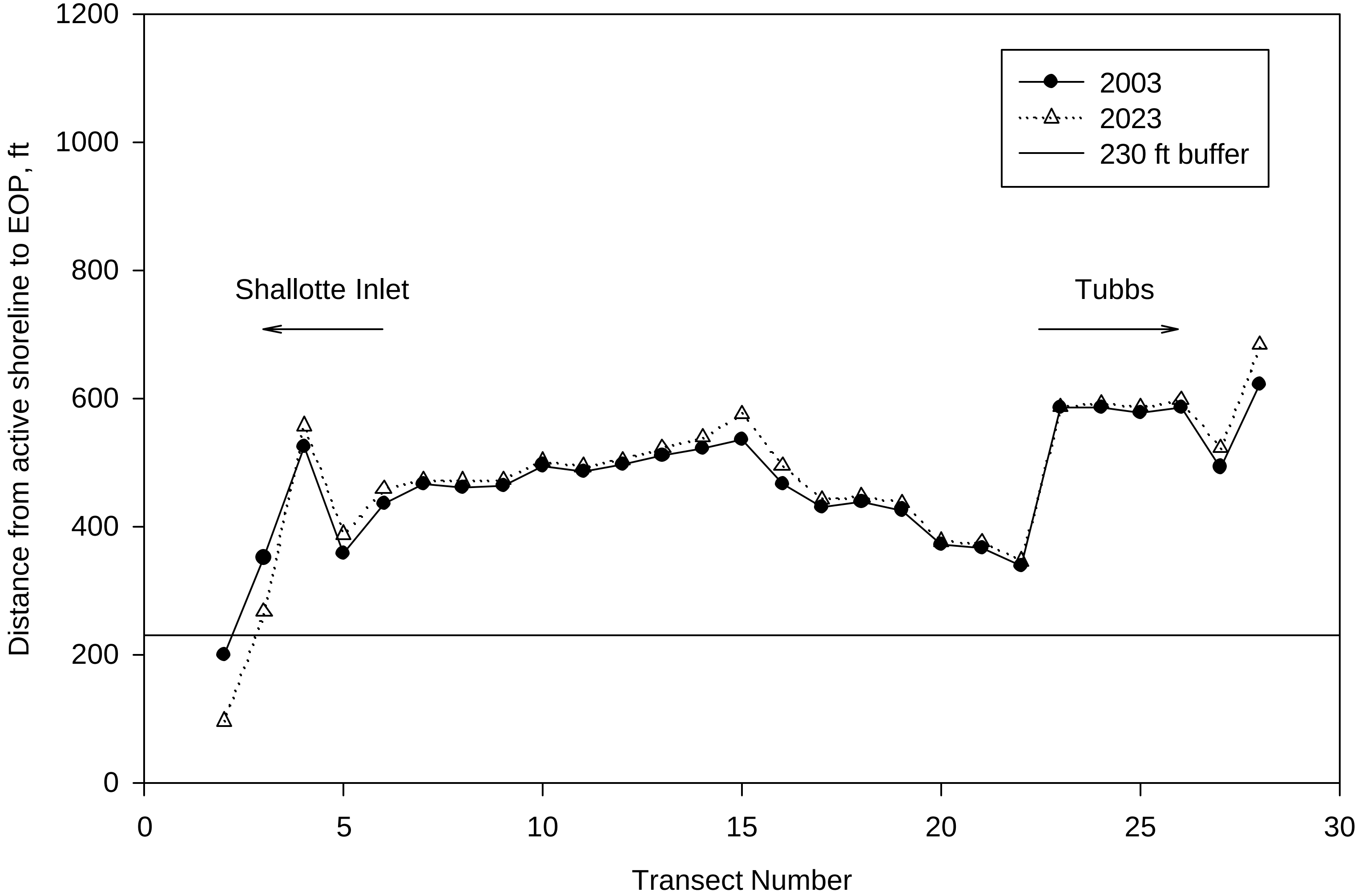

Figure 4. Distance from edge of pavement (EOP) to the active shoreline on Ocean Isle.

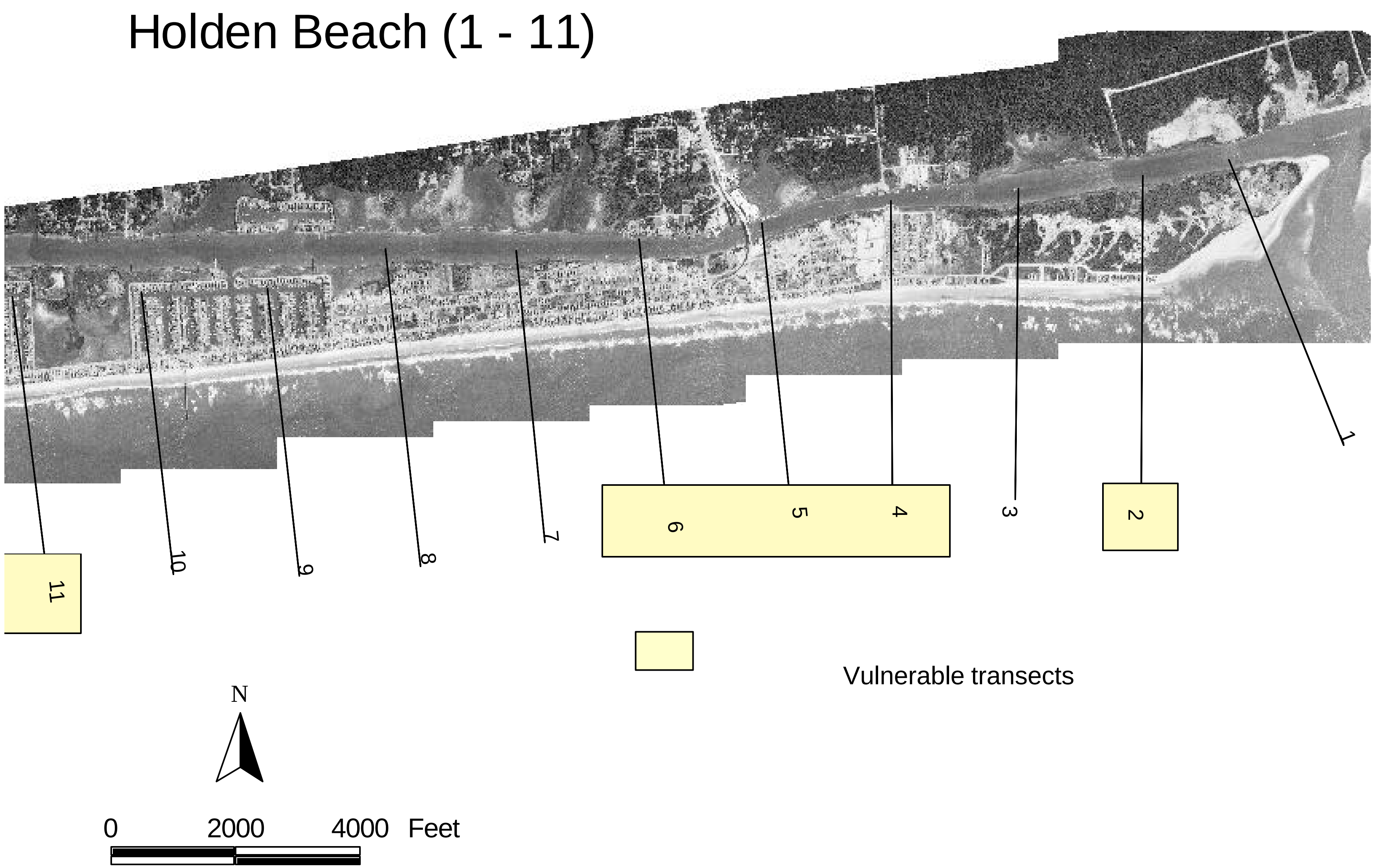

Figure 5a. Transect locations on Holden Beach.

Holden Beach (12 - 21)

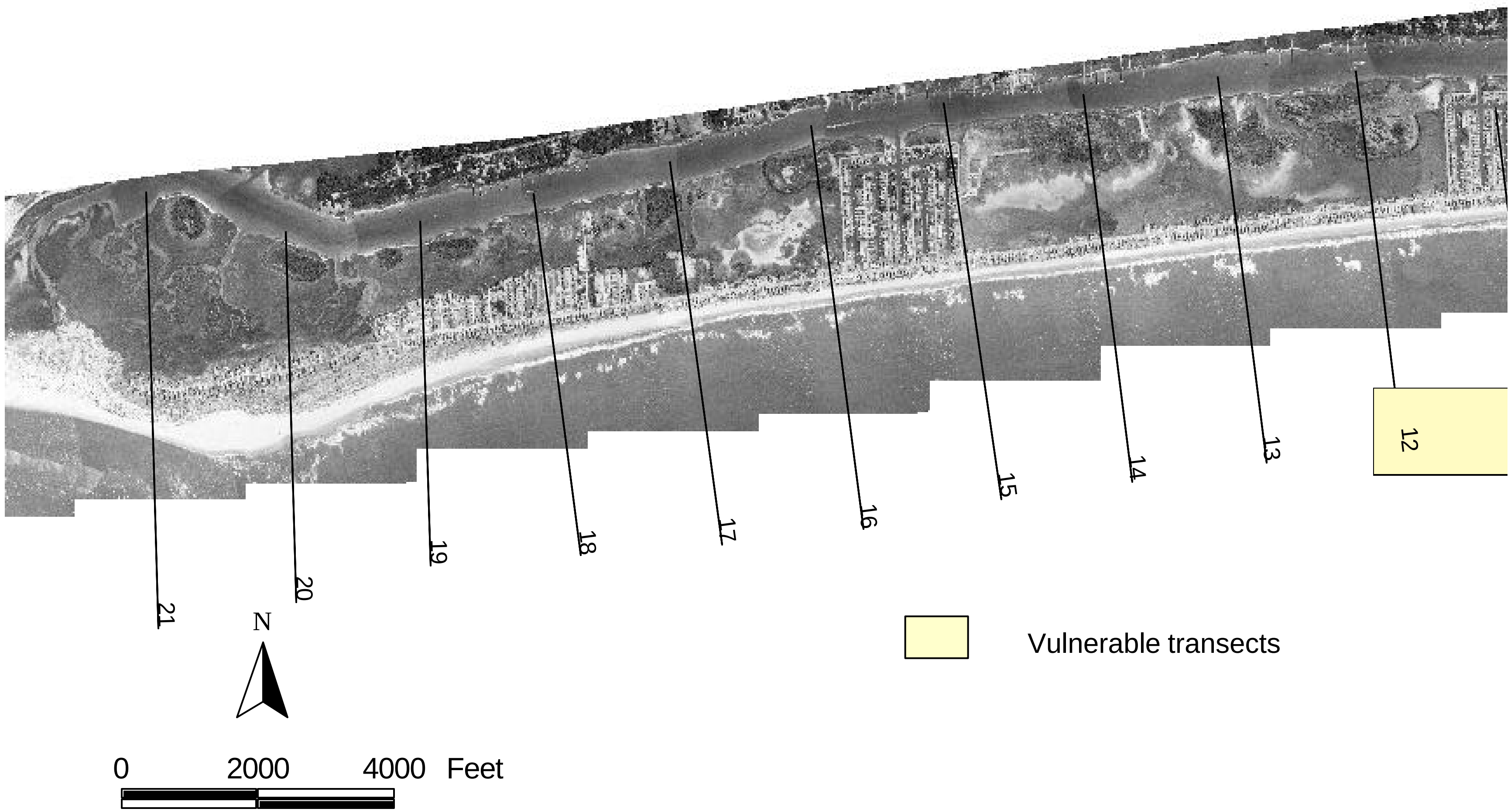

Figure 5b. Transect locations on Holden Beach.

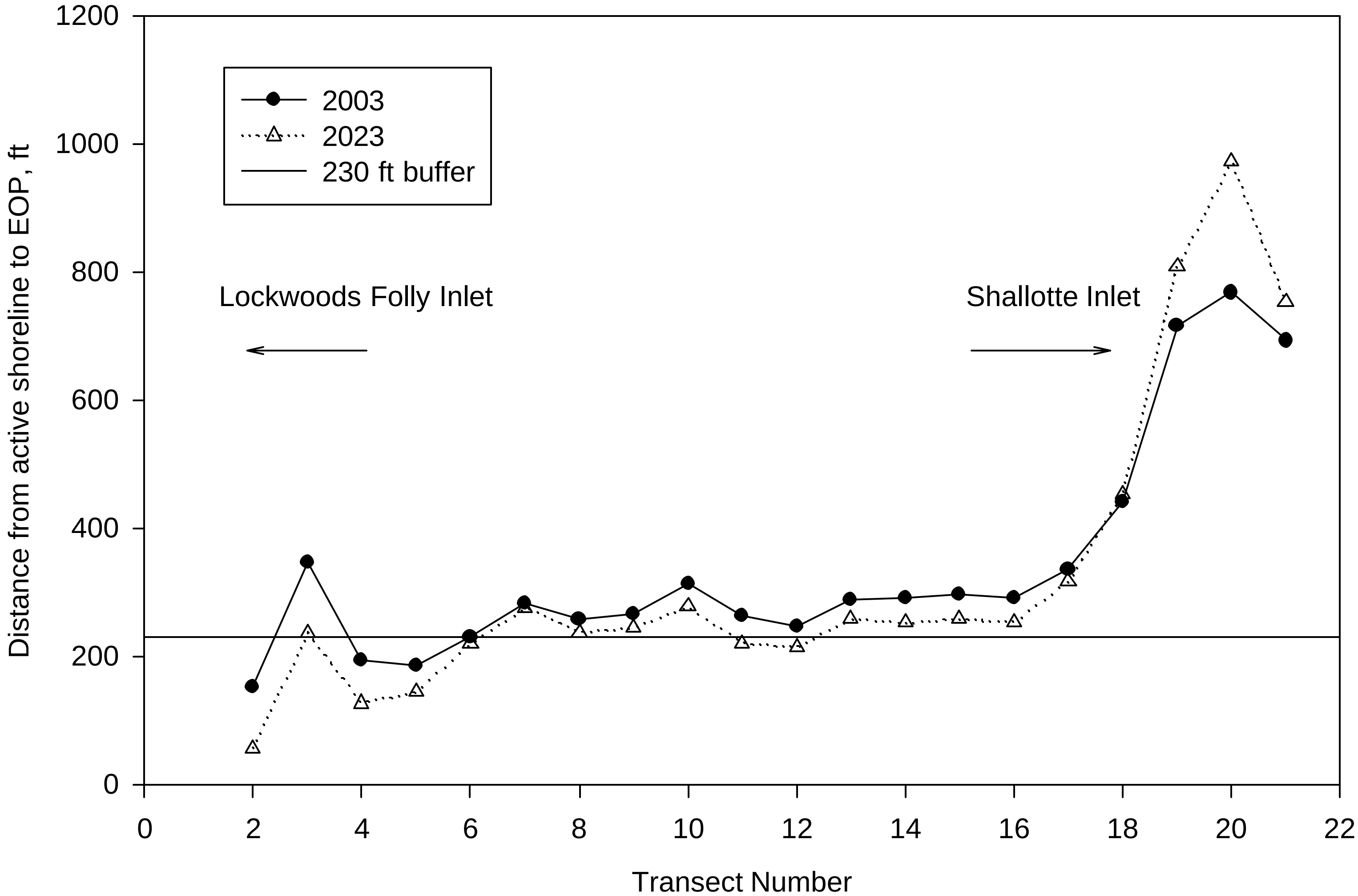

Figure 6. Distance from edge of pavement (EOP) to the active shoreline on Holden Beach.

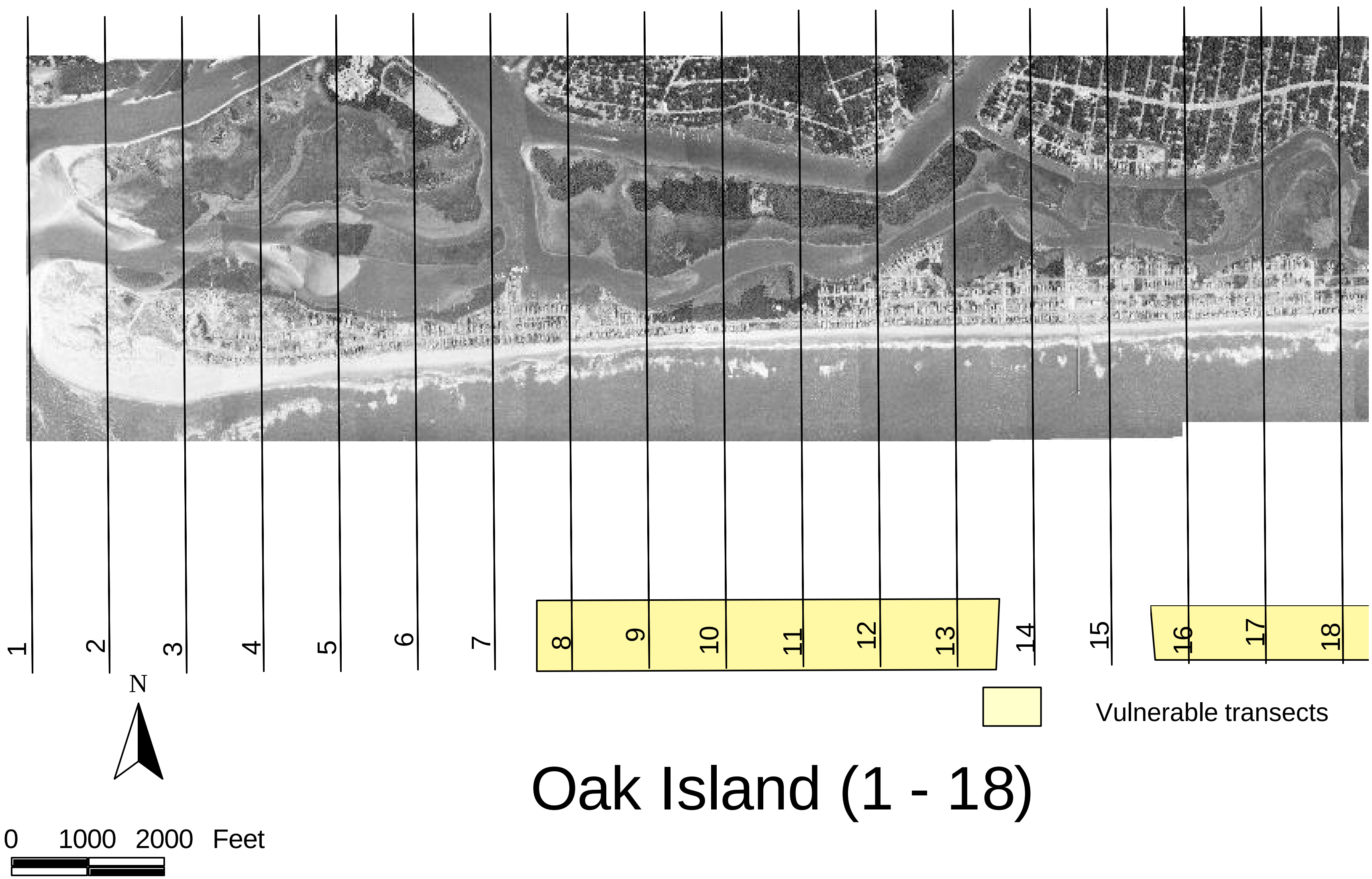

Figure 7a. Transect locations on Oak Island.

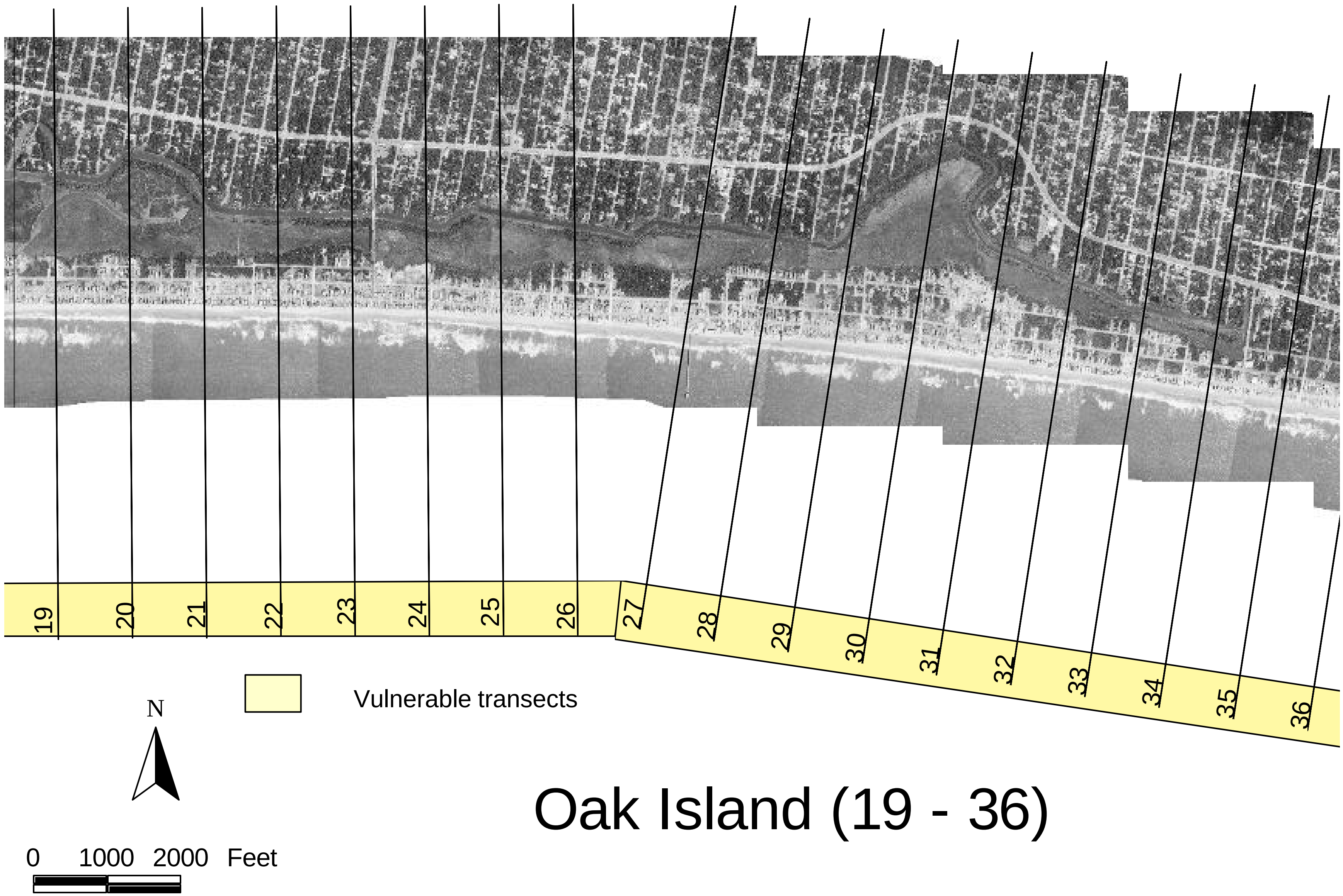

Figure 7b. Transect locations on Oak Island.

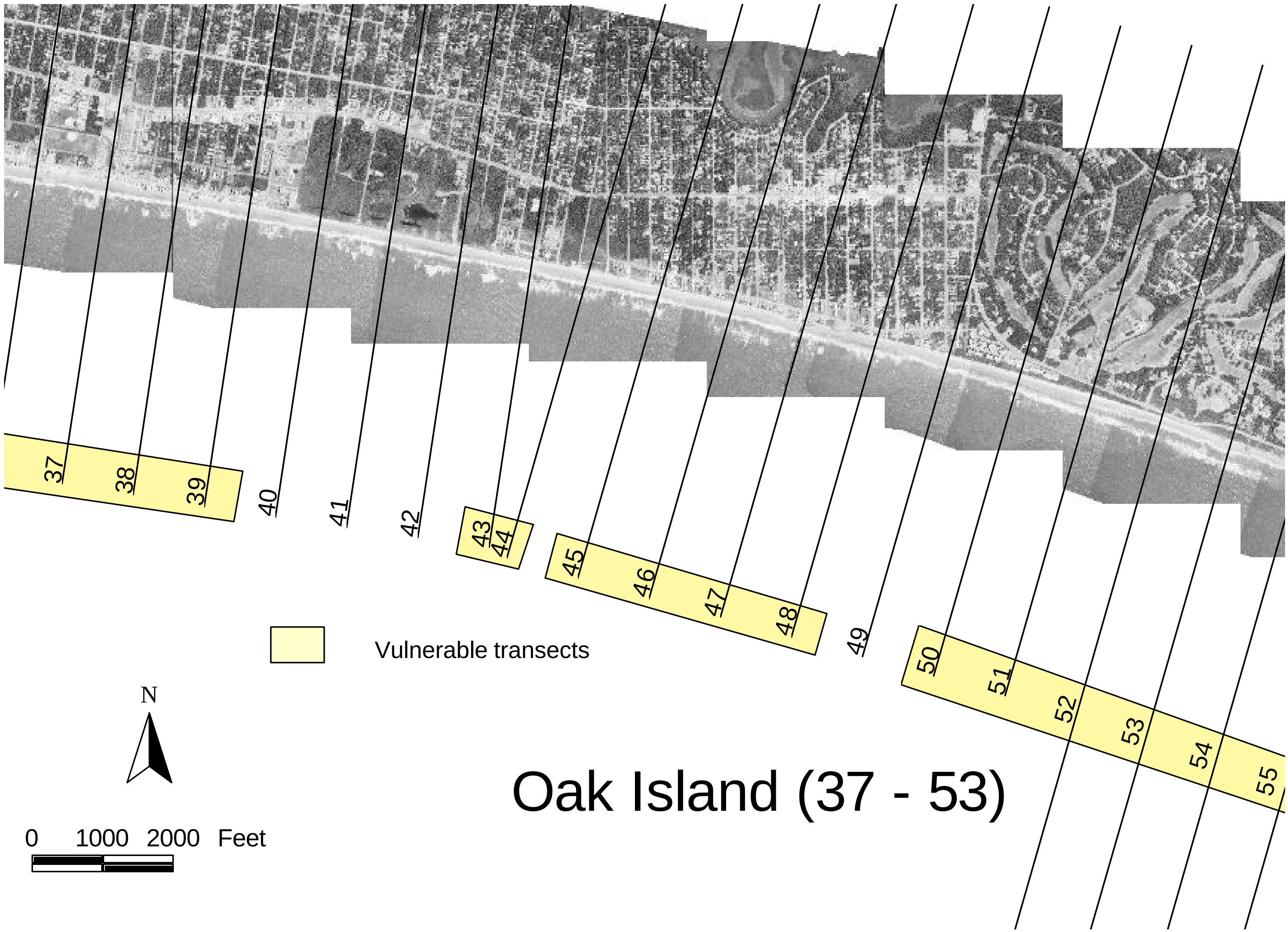

Figure 7c. Transect locations on Oak Island.

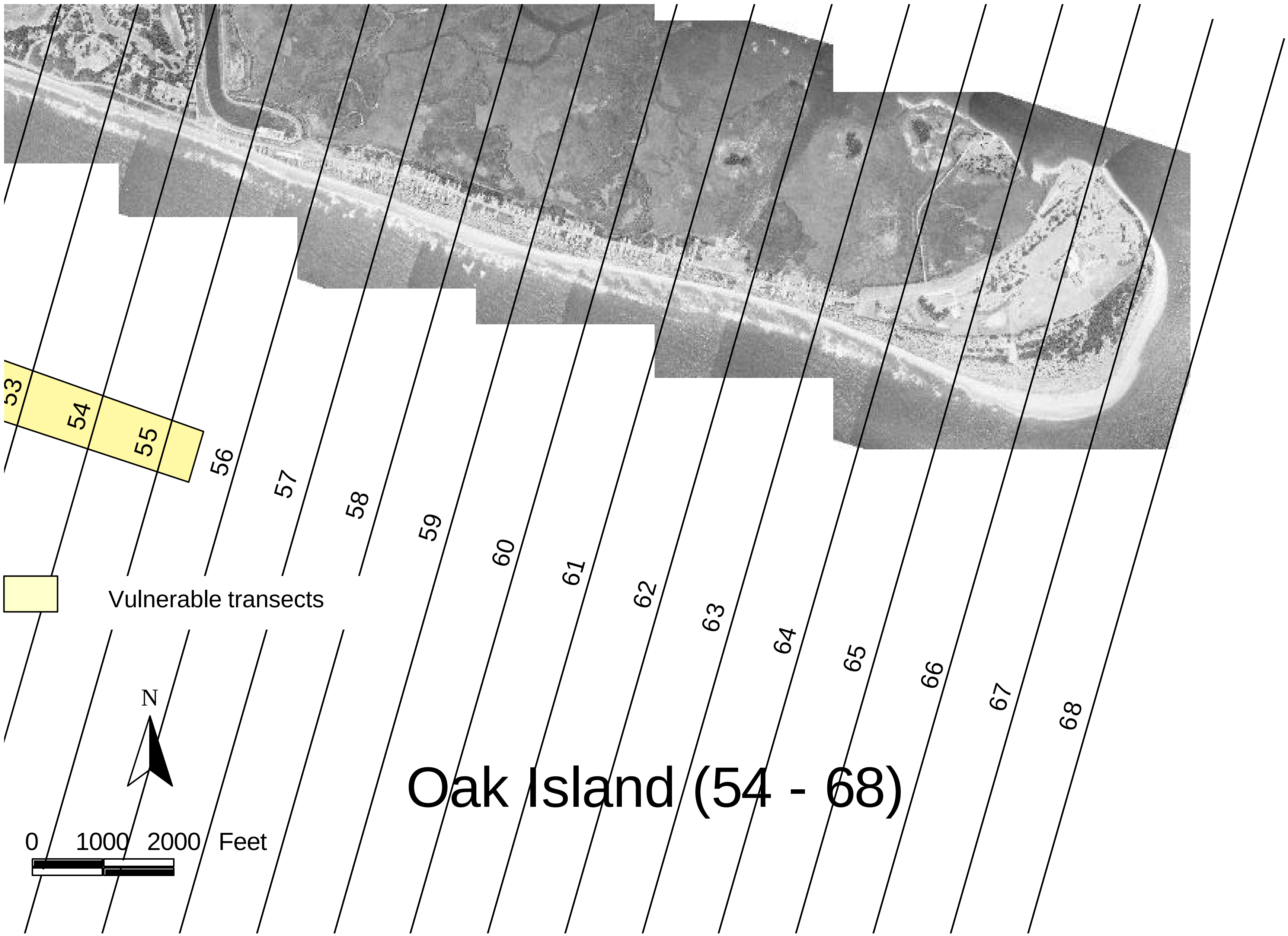

Figure 7d. Transect locations on Oak Island.

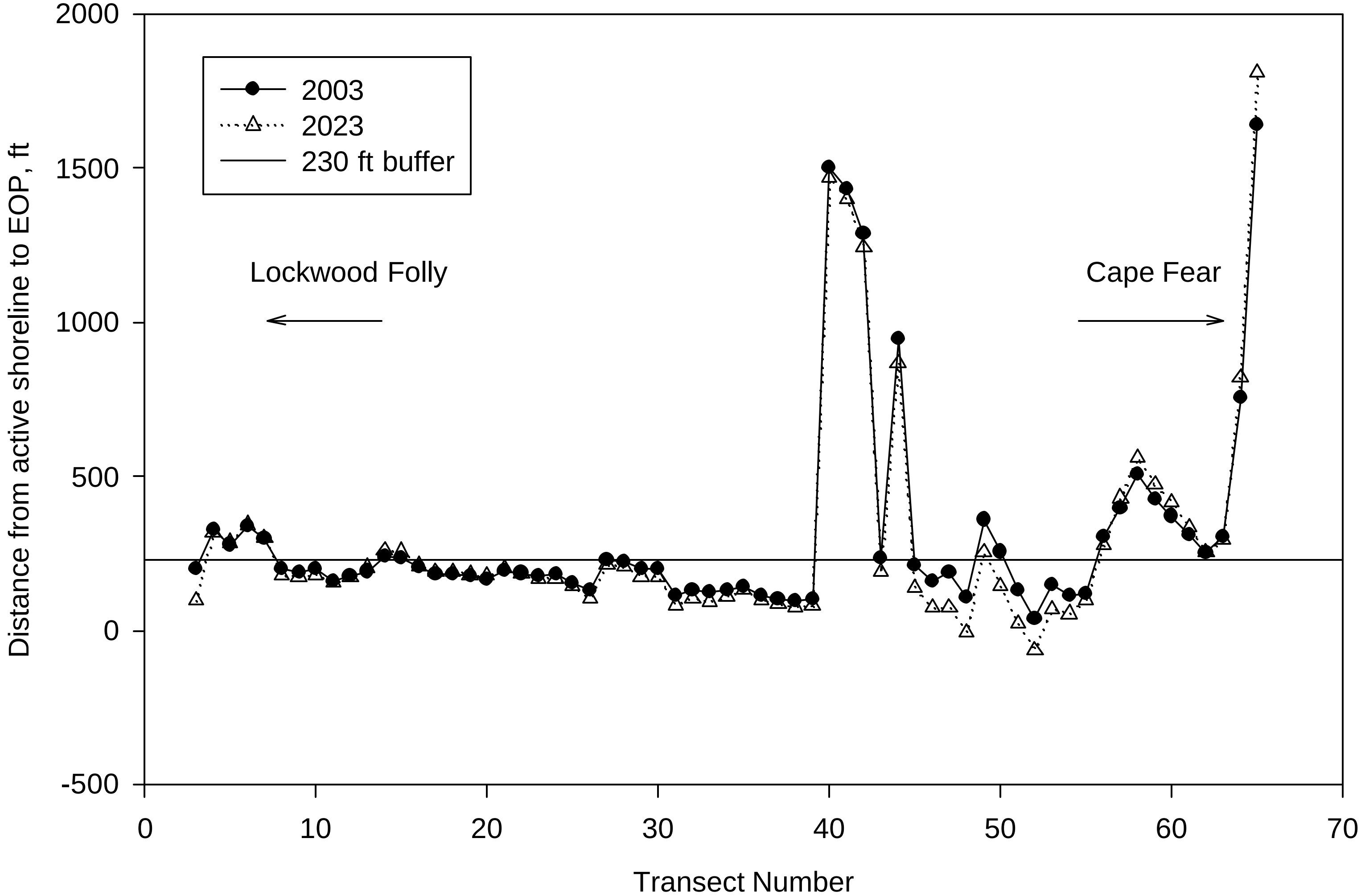

Figure 8. Distance from edge of pavement (EOP) to the active shoreline on Oak Island.

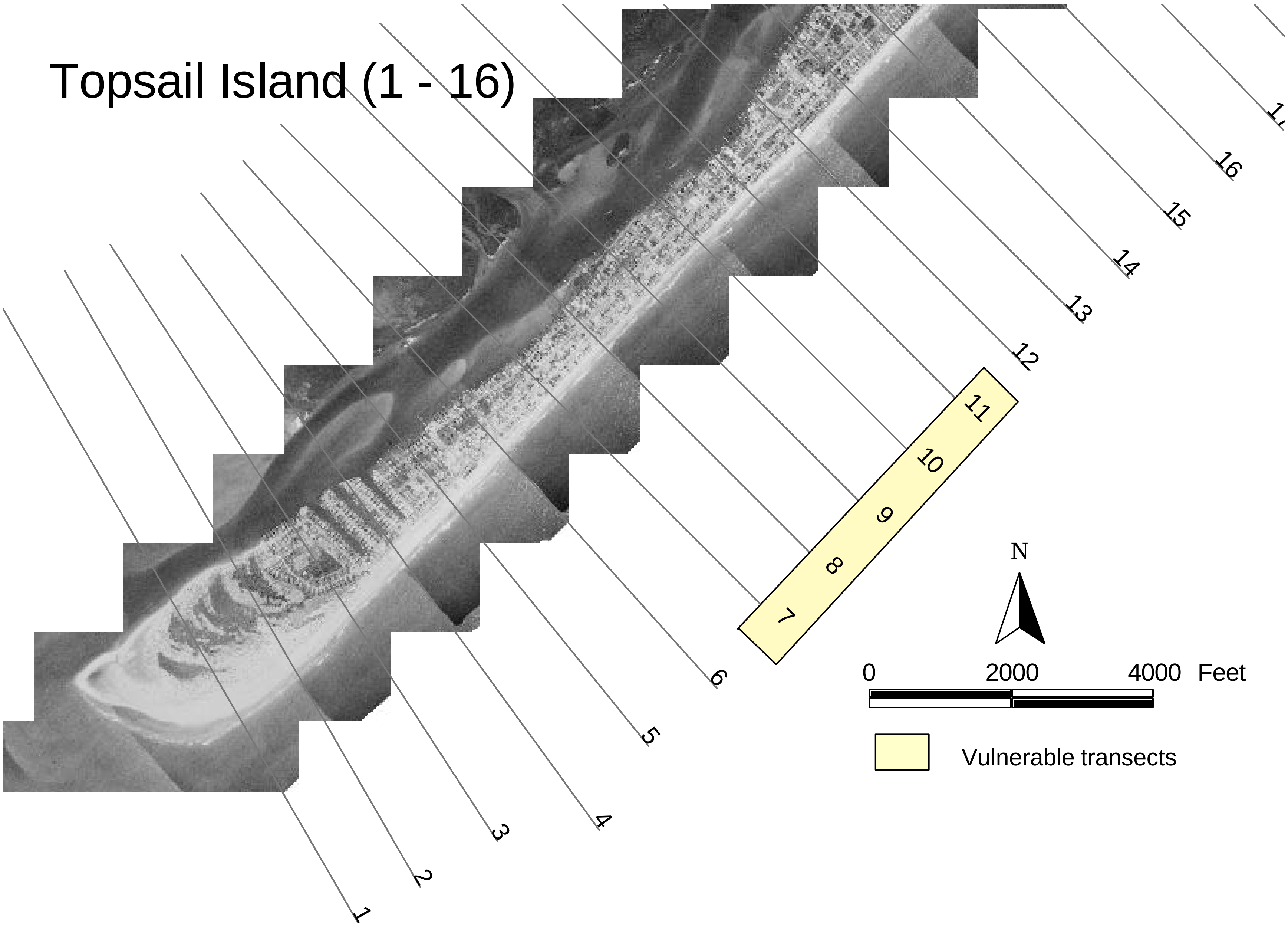

Figure 9a. Transect locations on Topsail Island.

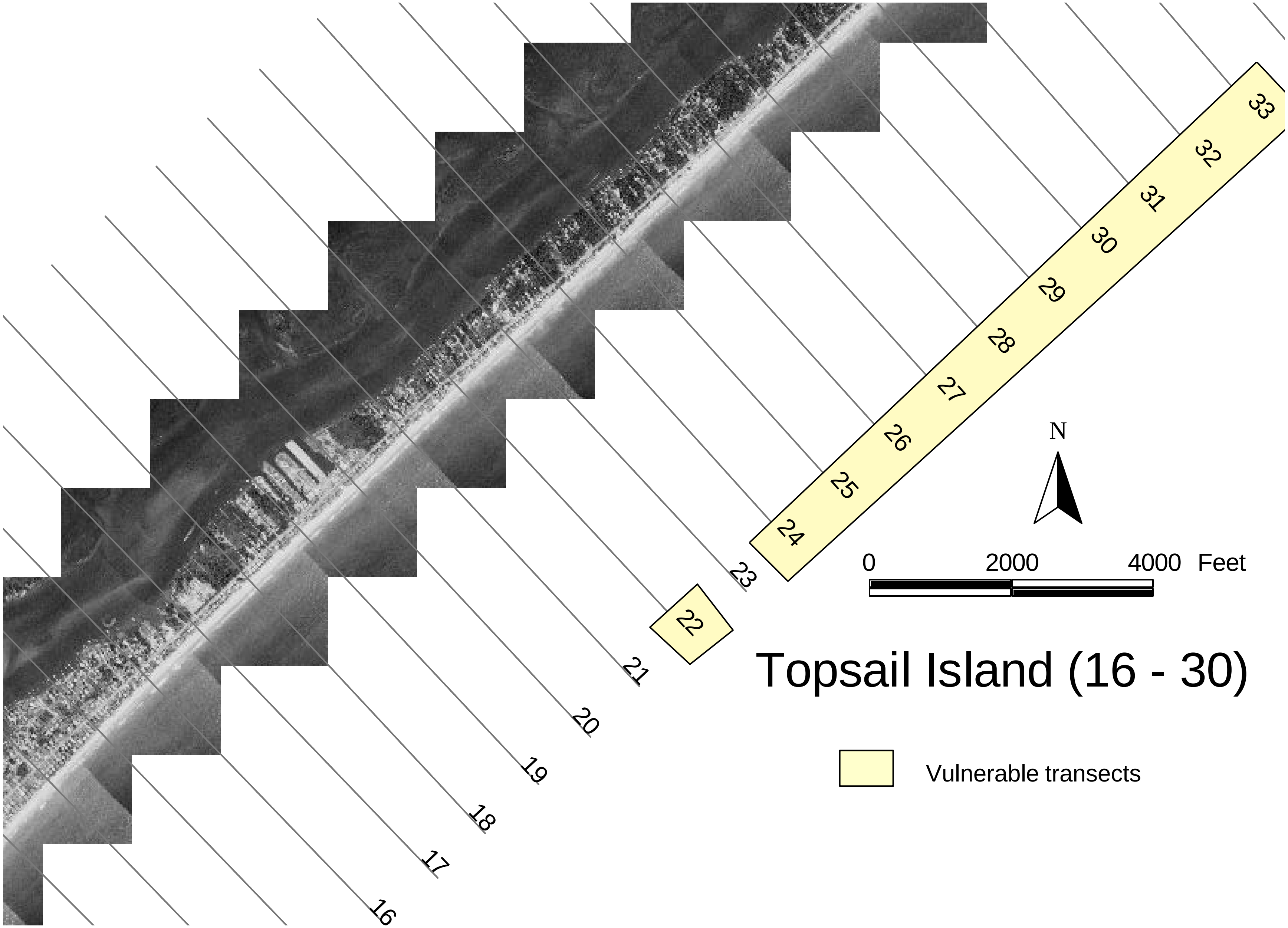

Figure 9b. Transect locations on Topsail Island.

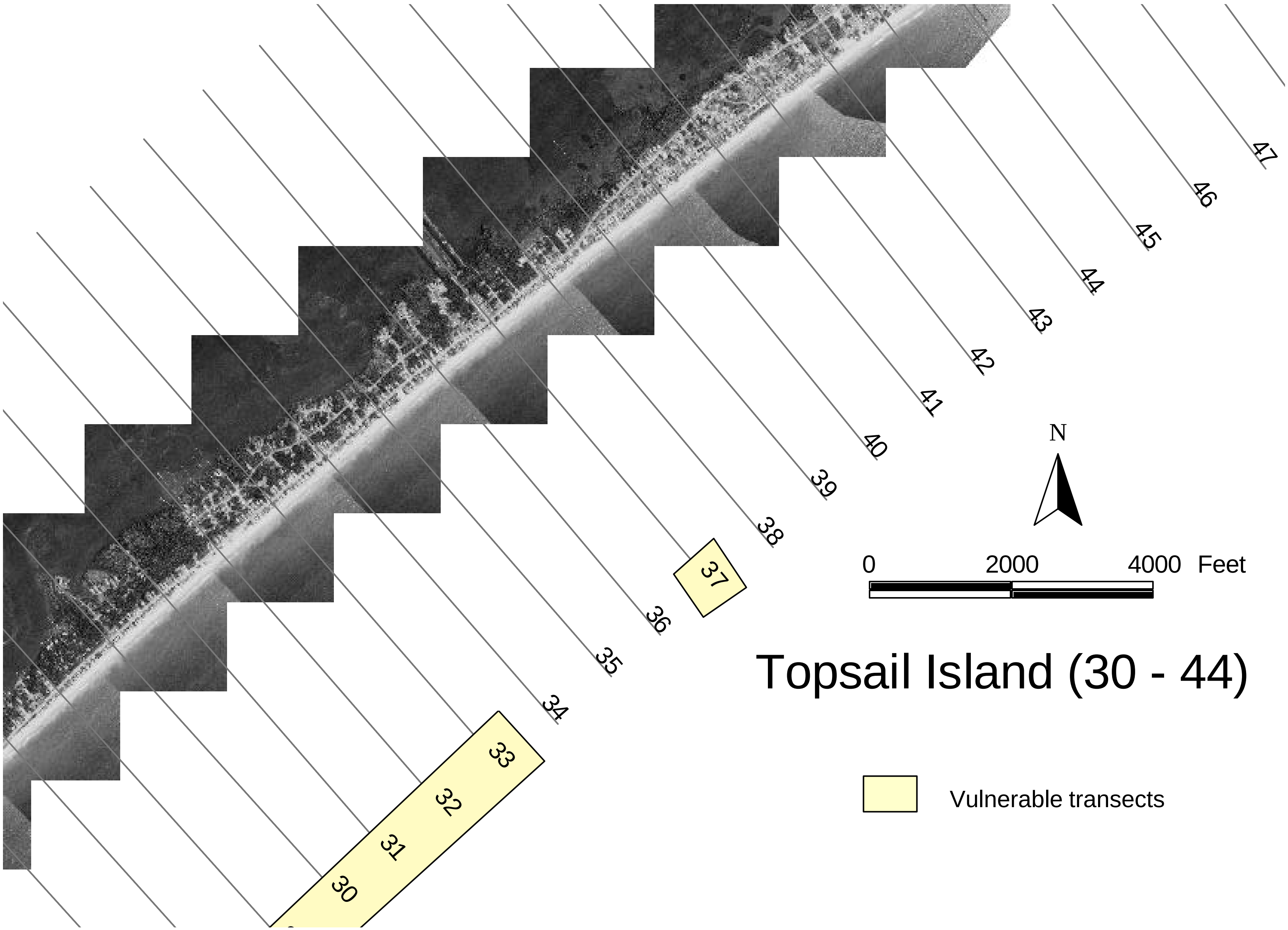

Figure 9c. Transect locations on Topsail Island.

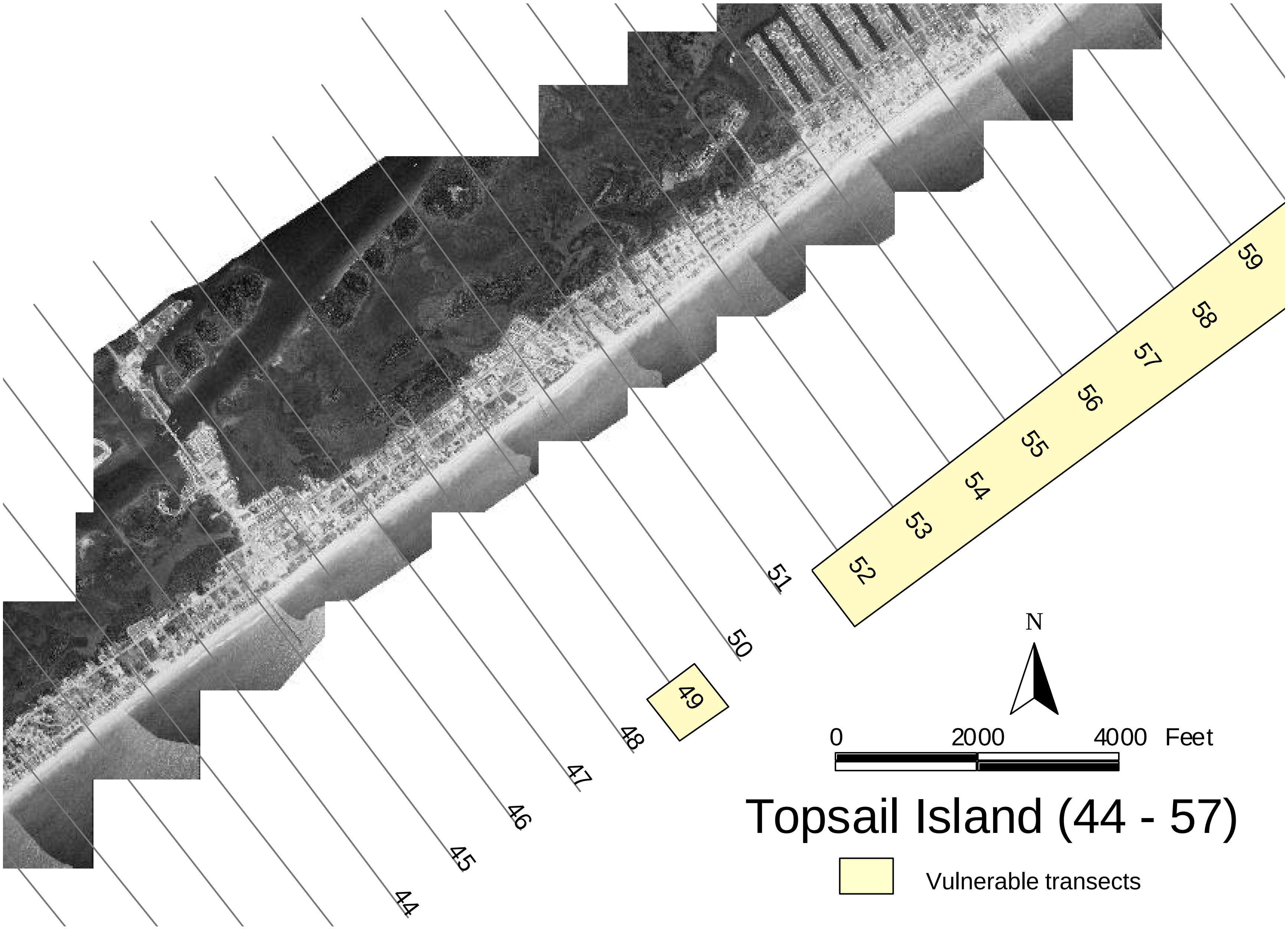

Figure 9d. Transect locations on Topsail Island.

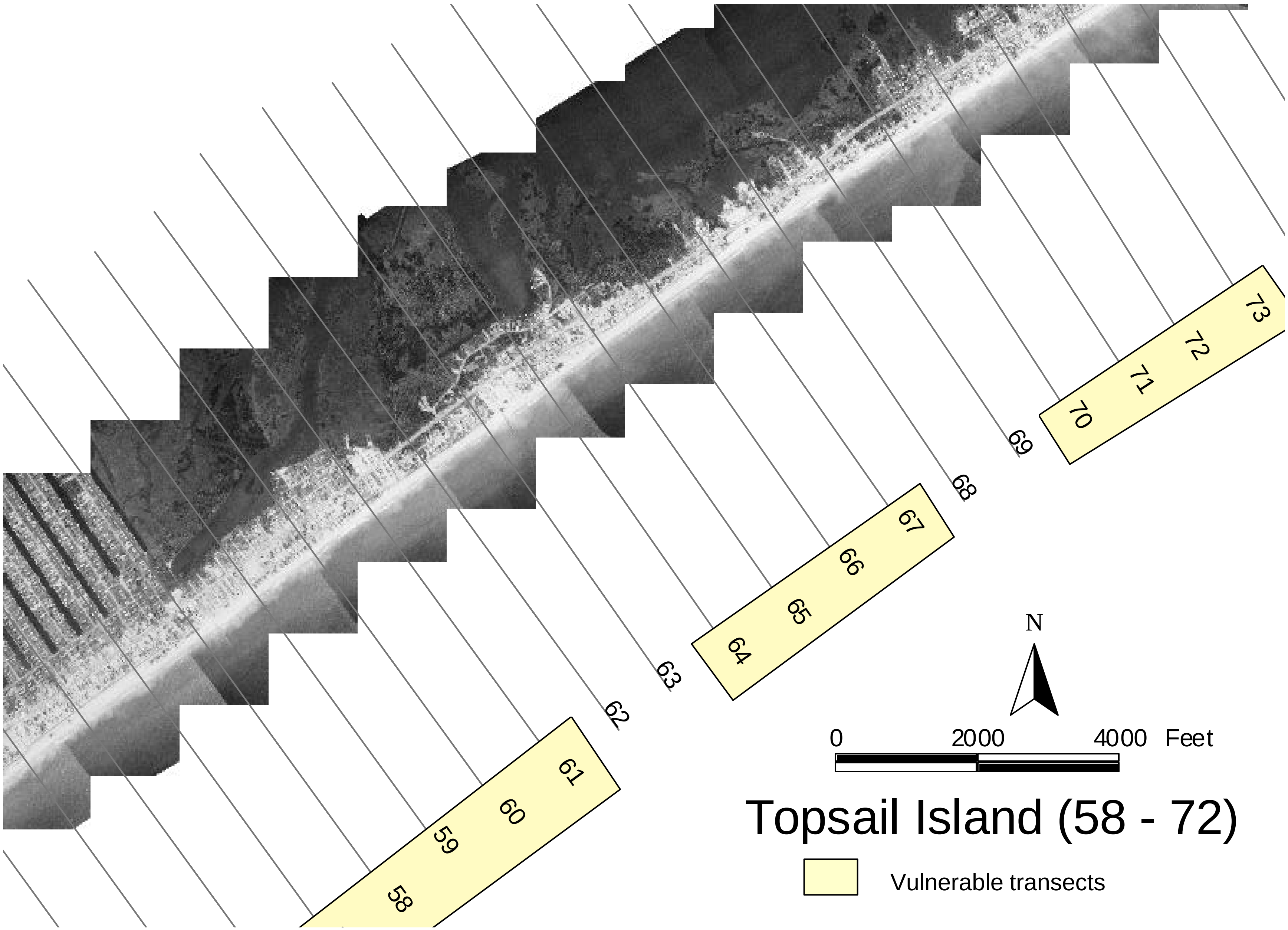

Figure 9e. Transect locations on Topsail Island.

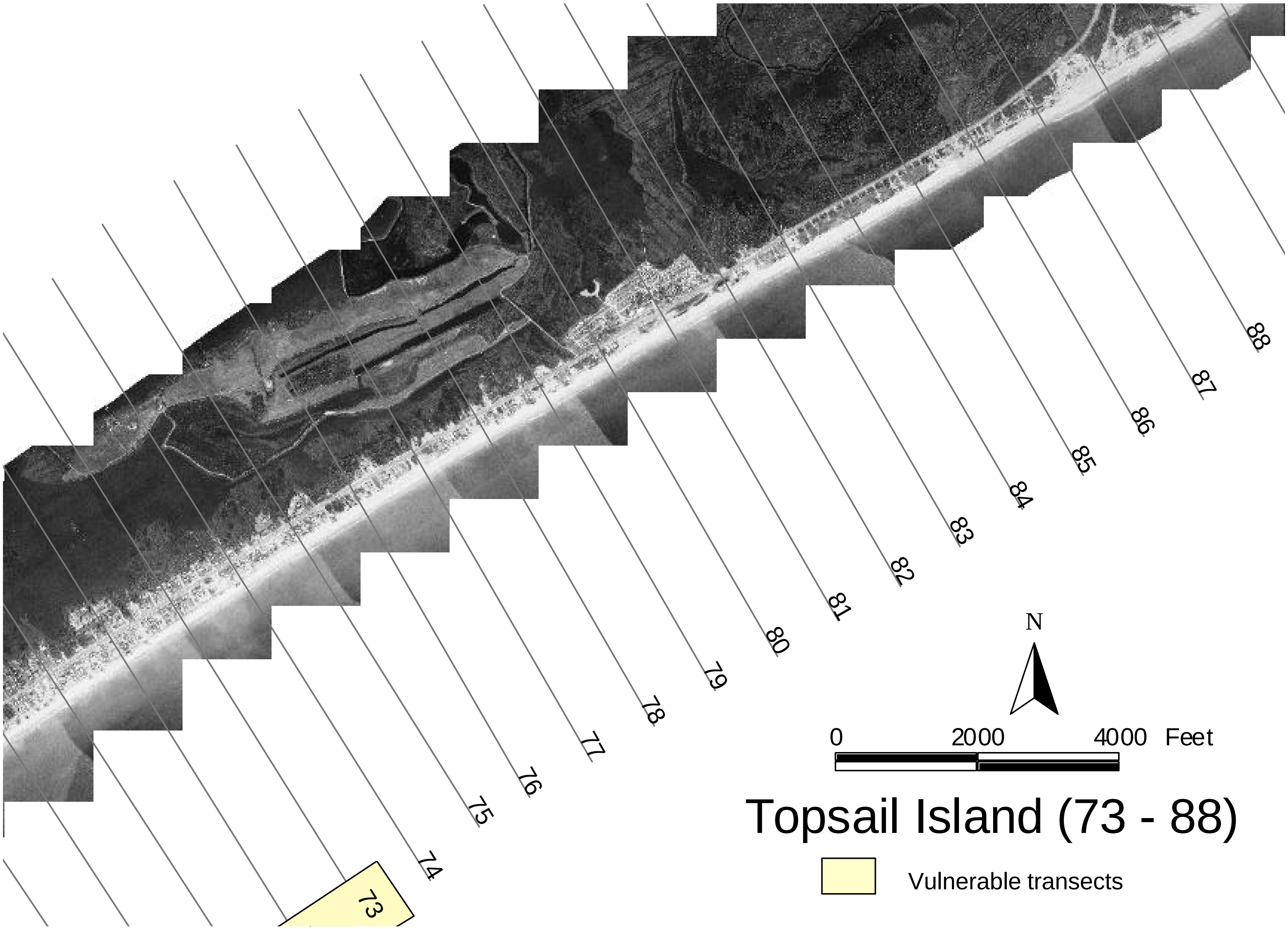

Figure 9f. Transect locations on Topsail Island.

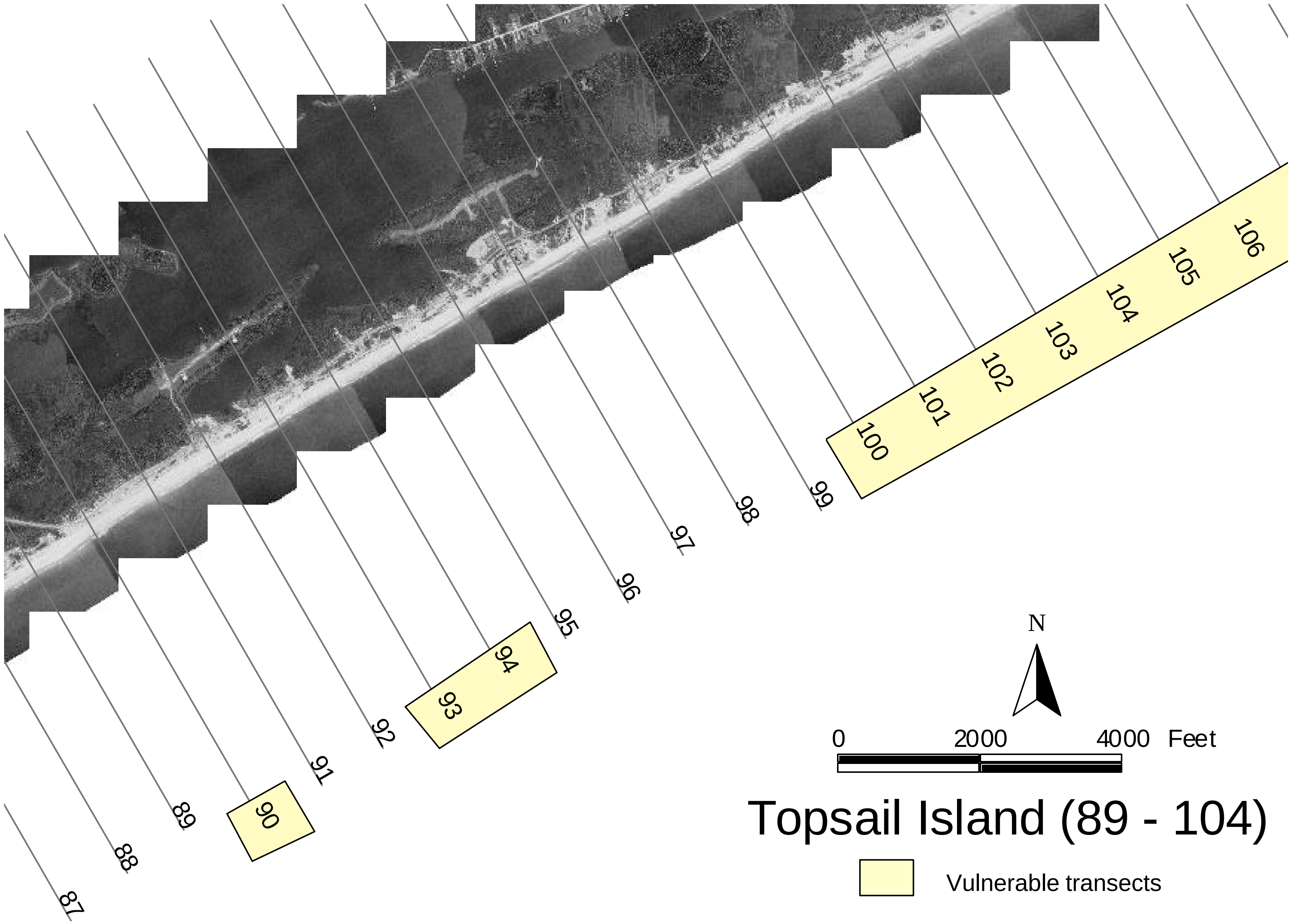

Figure 9g. Transect locations on Topsail Island.

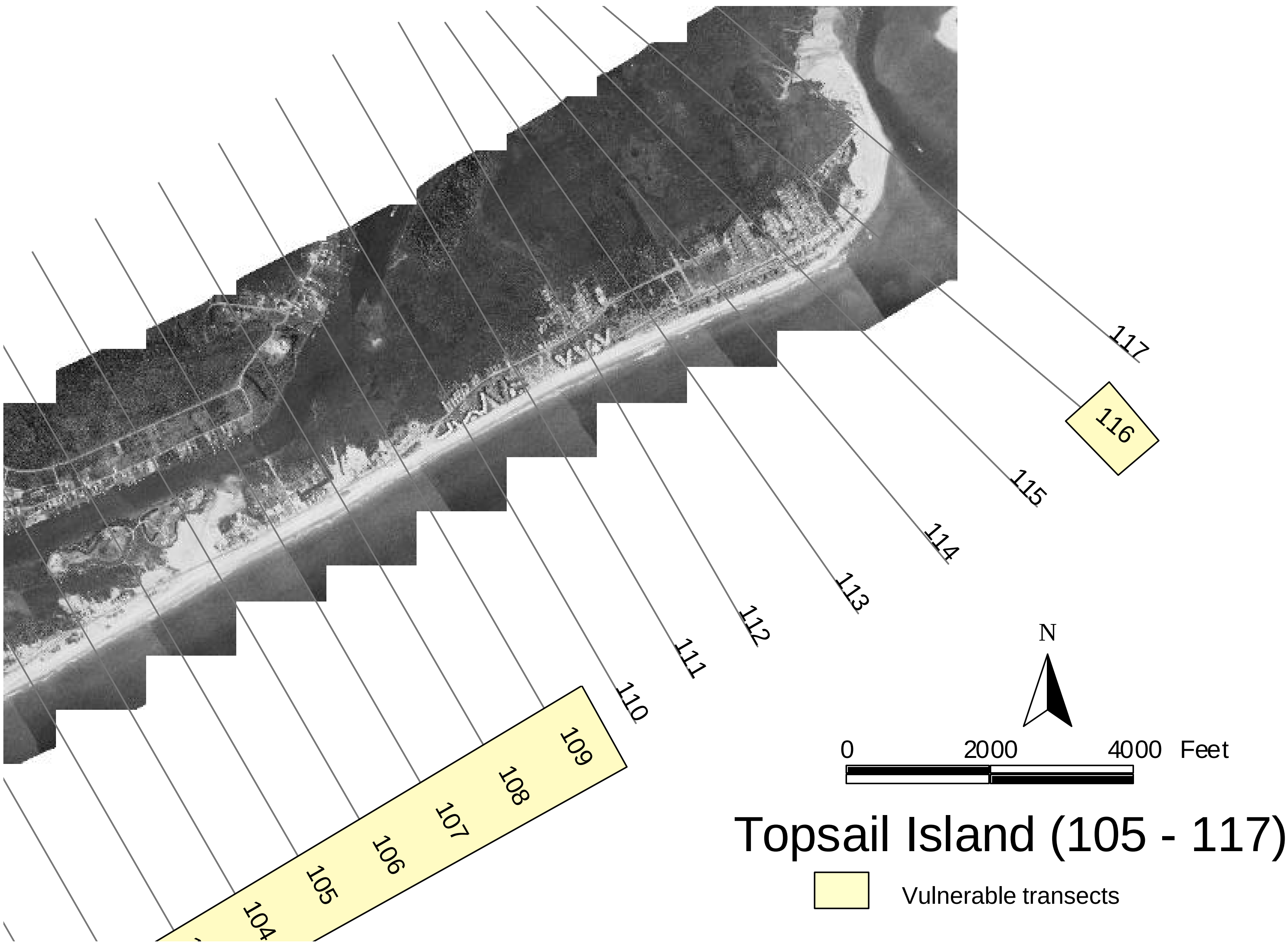

Figure 9h. Transect locations on Topsail Island.

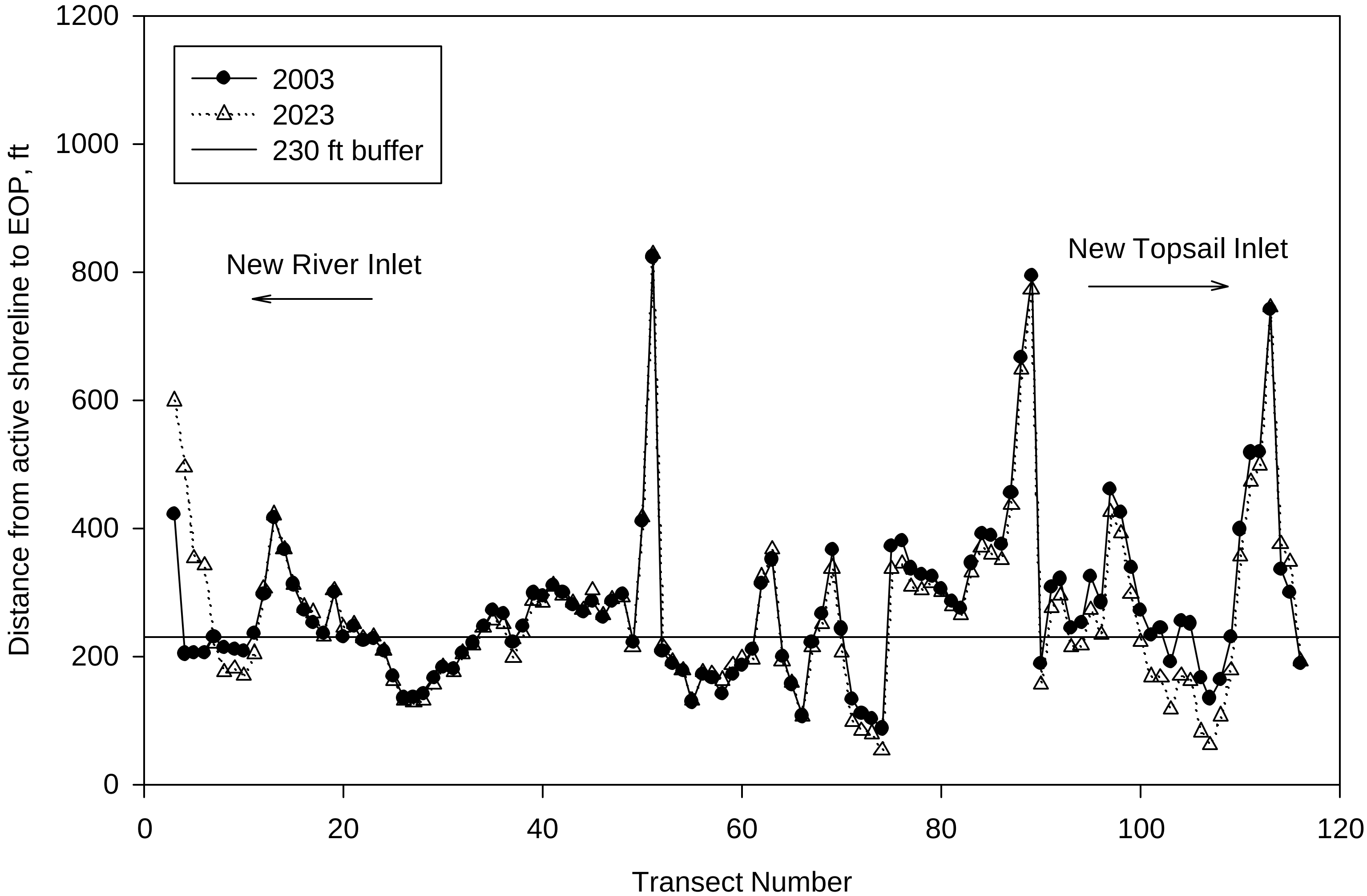

Figure 10. Distance from edge of pavement (EOP) to the active shoreline on Topsail Island.

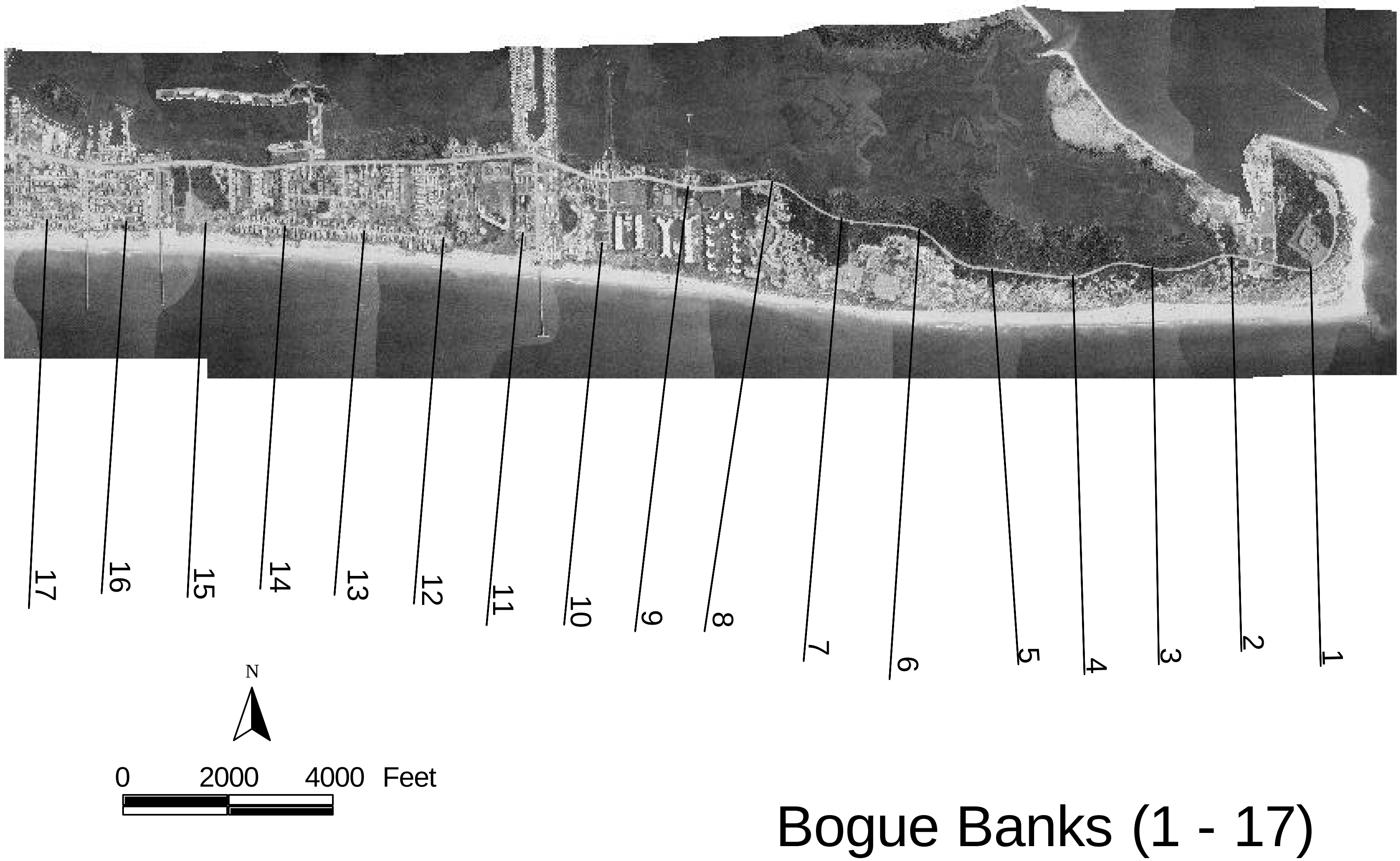

Figure 11a. Transect locations on Bogue Banks.

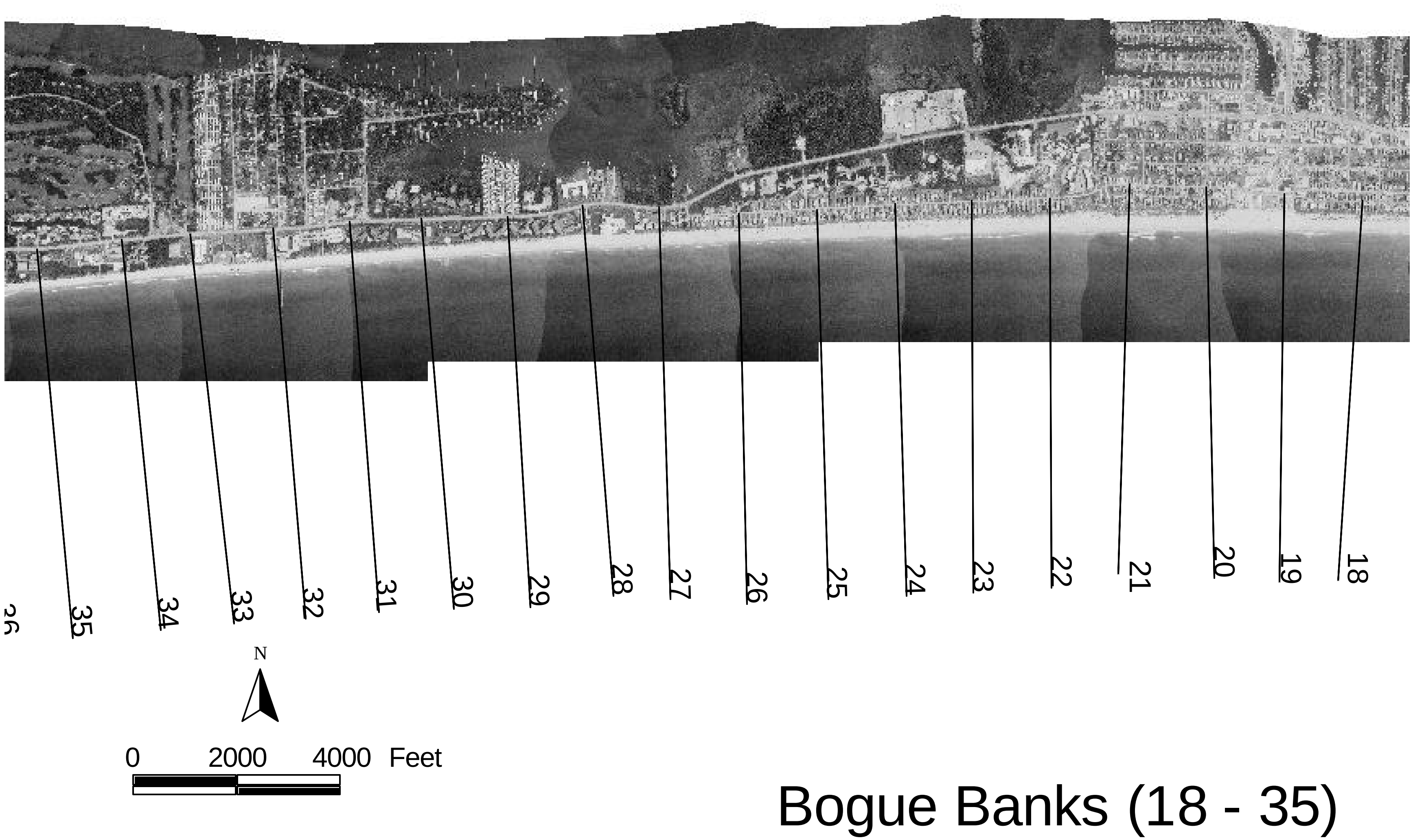

Figure 11b. Transect locations on Bogue Banks.

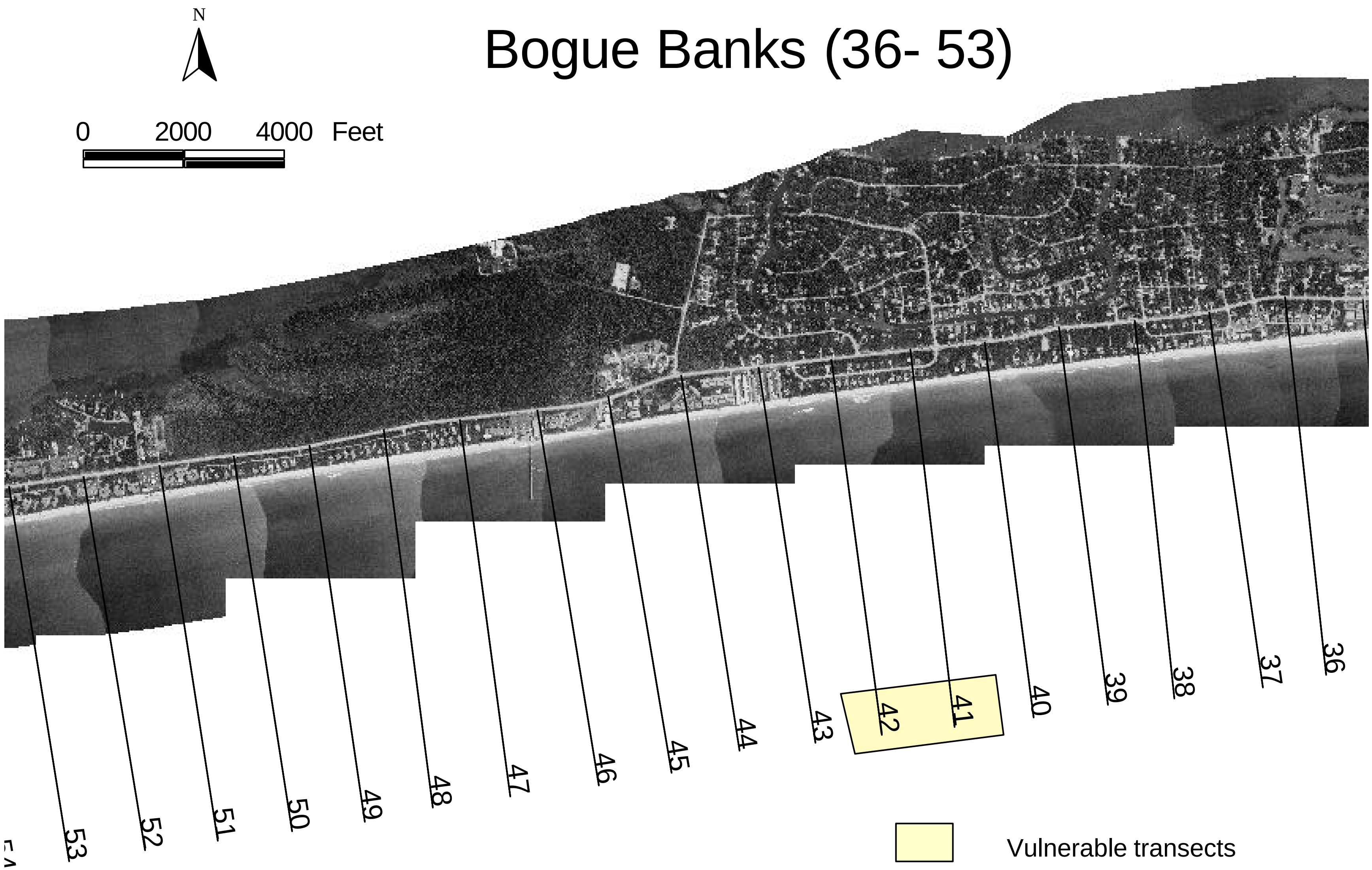

Figure 11c. Transect locations on Bogue Banks.

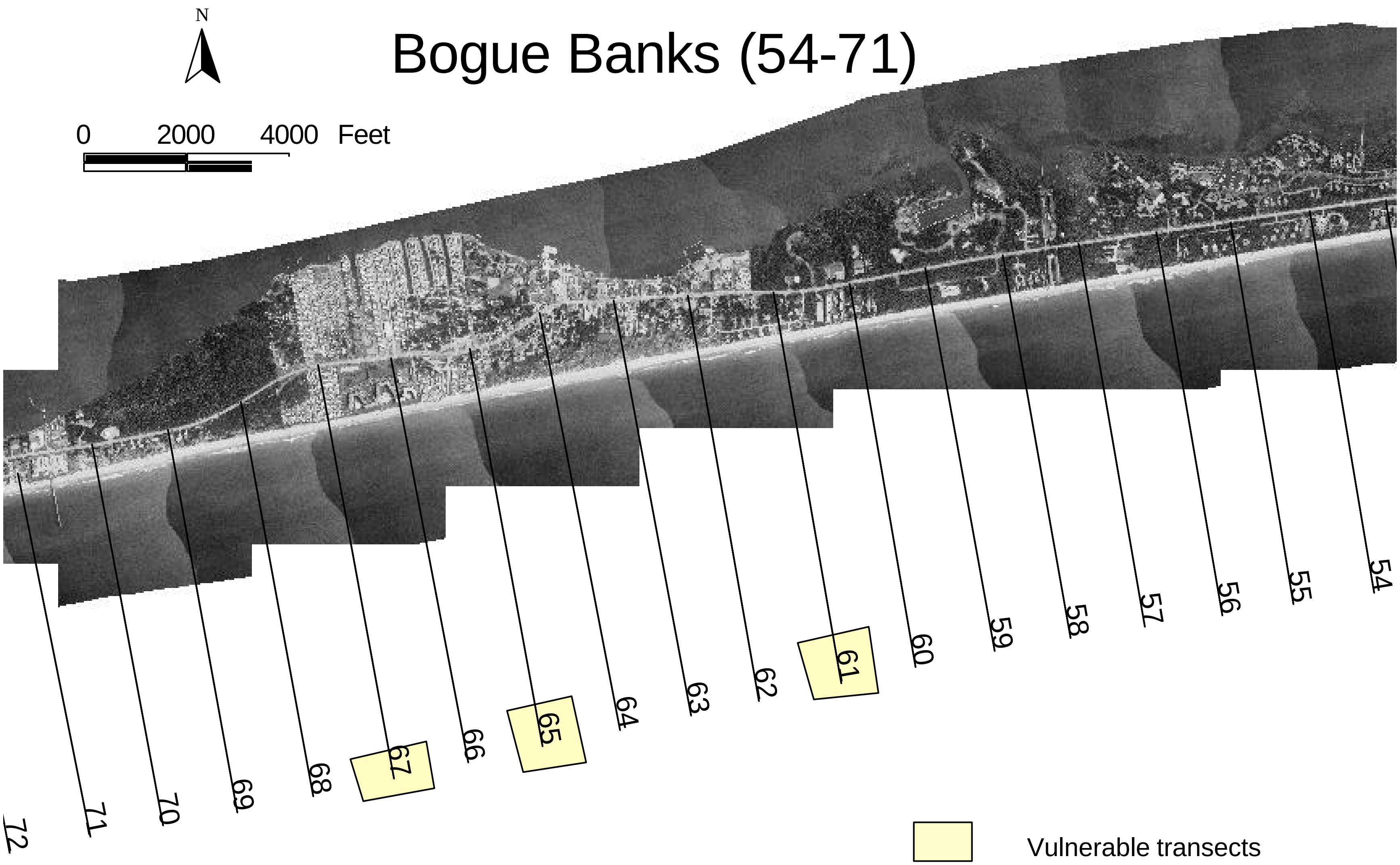

Figure 11d. Transect locations on Bogue Banks.

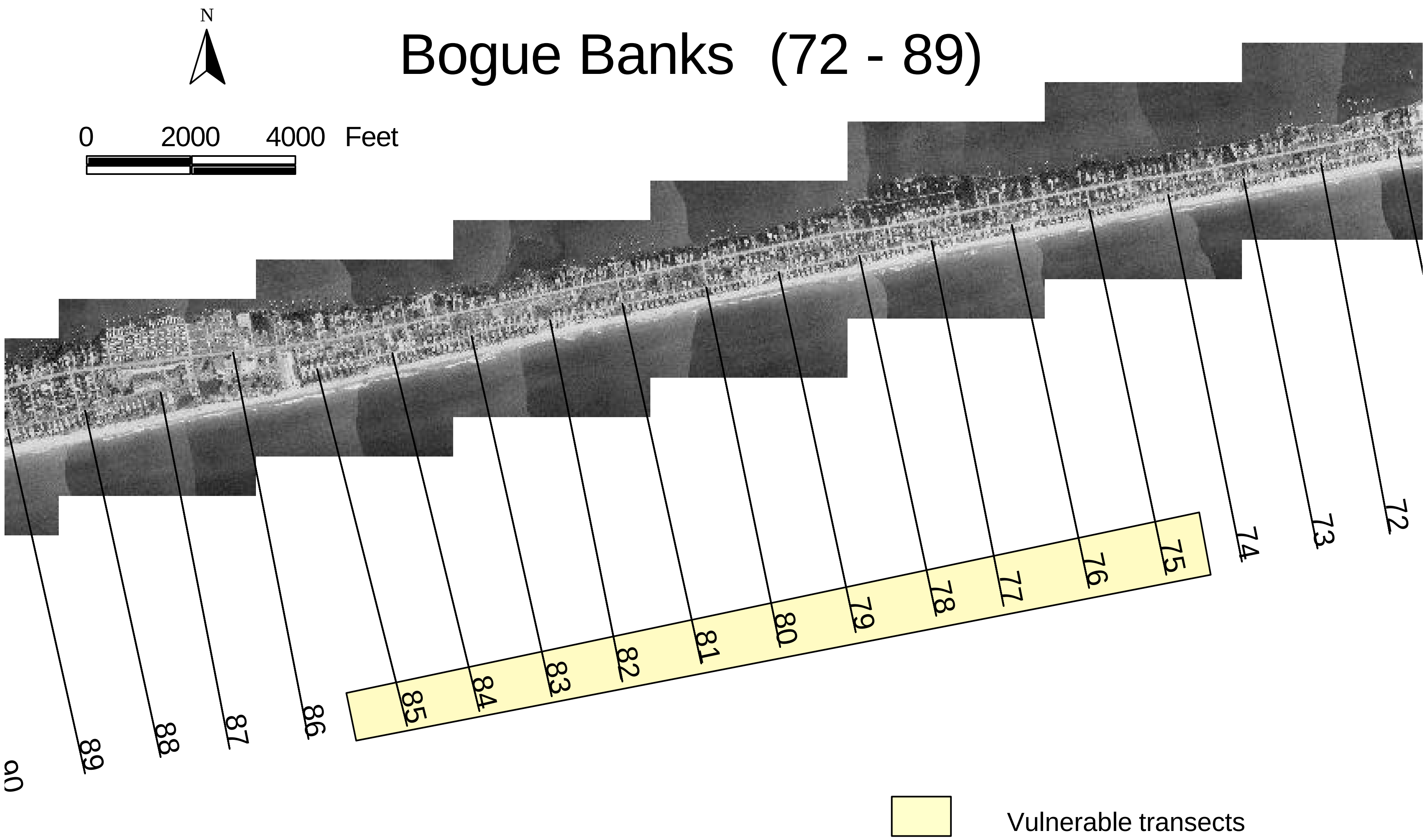

Figure 11e. Transect locations on Bogue Banks.

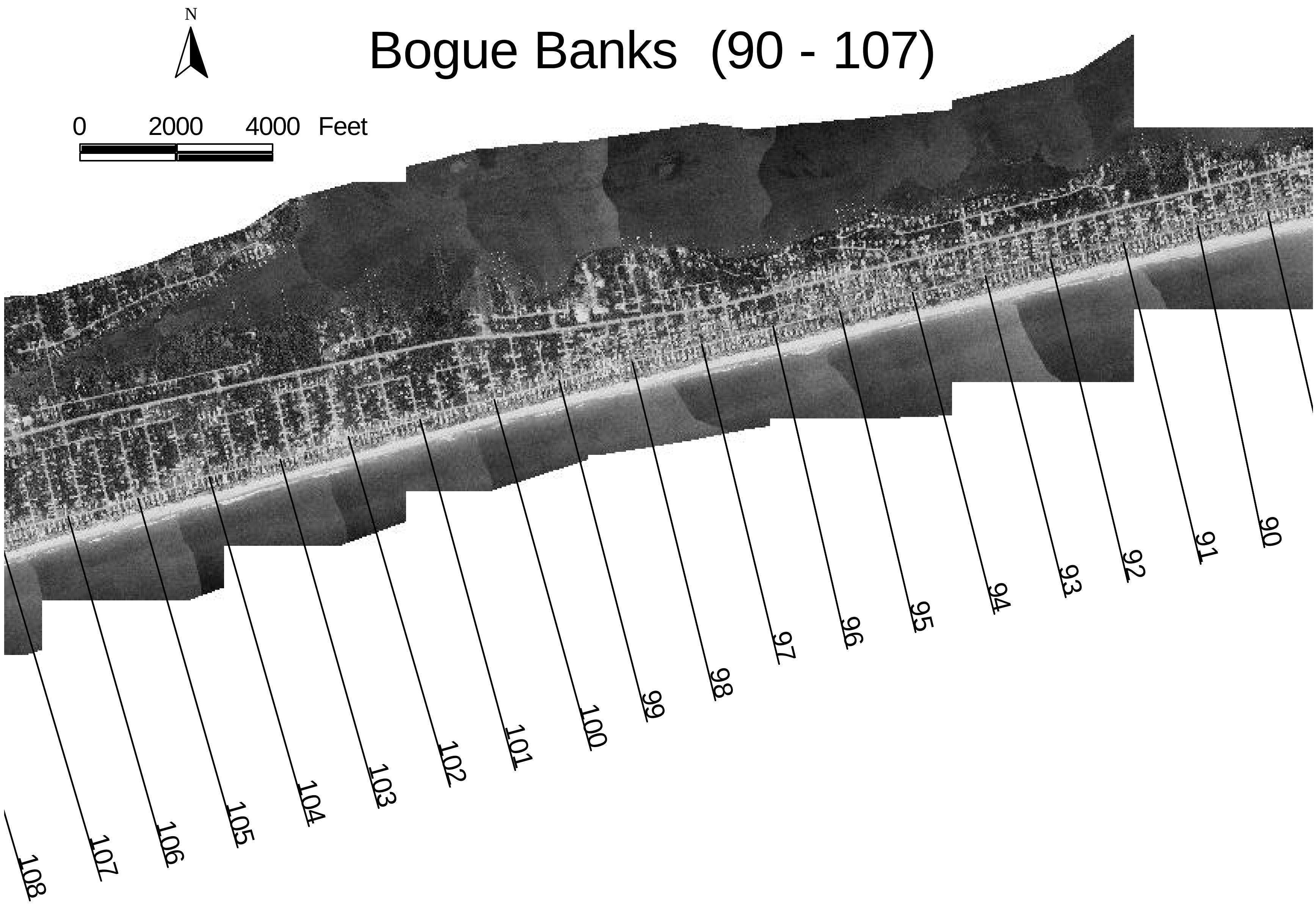

Figure 11f. Transect locations on Bogue Banks.

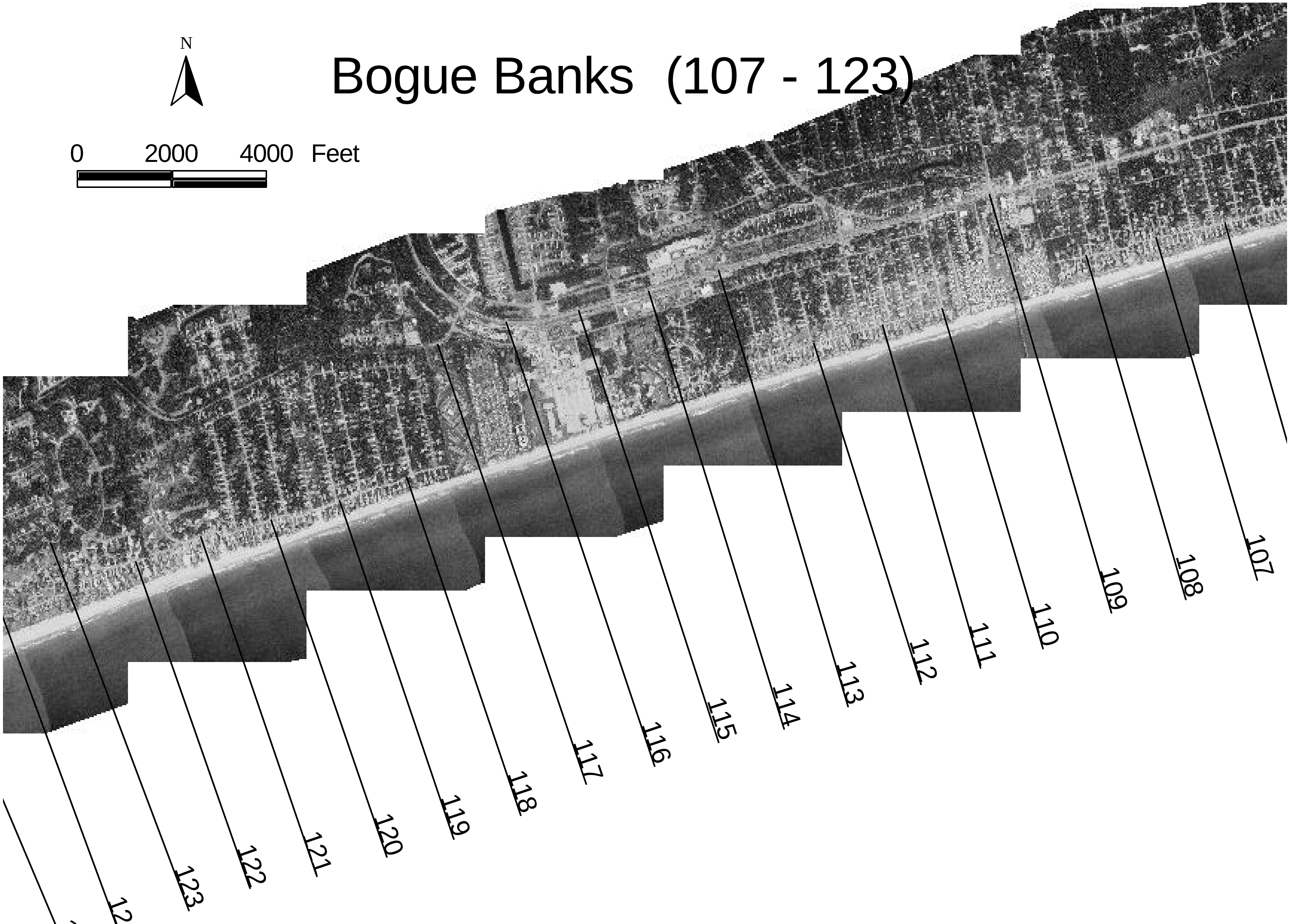

Figure 11g. Transect locations on Bogue Banks.

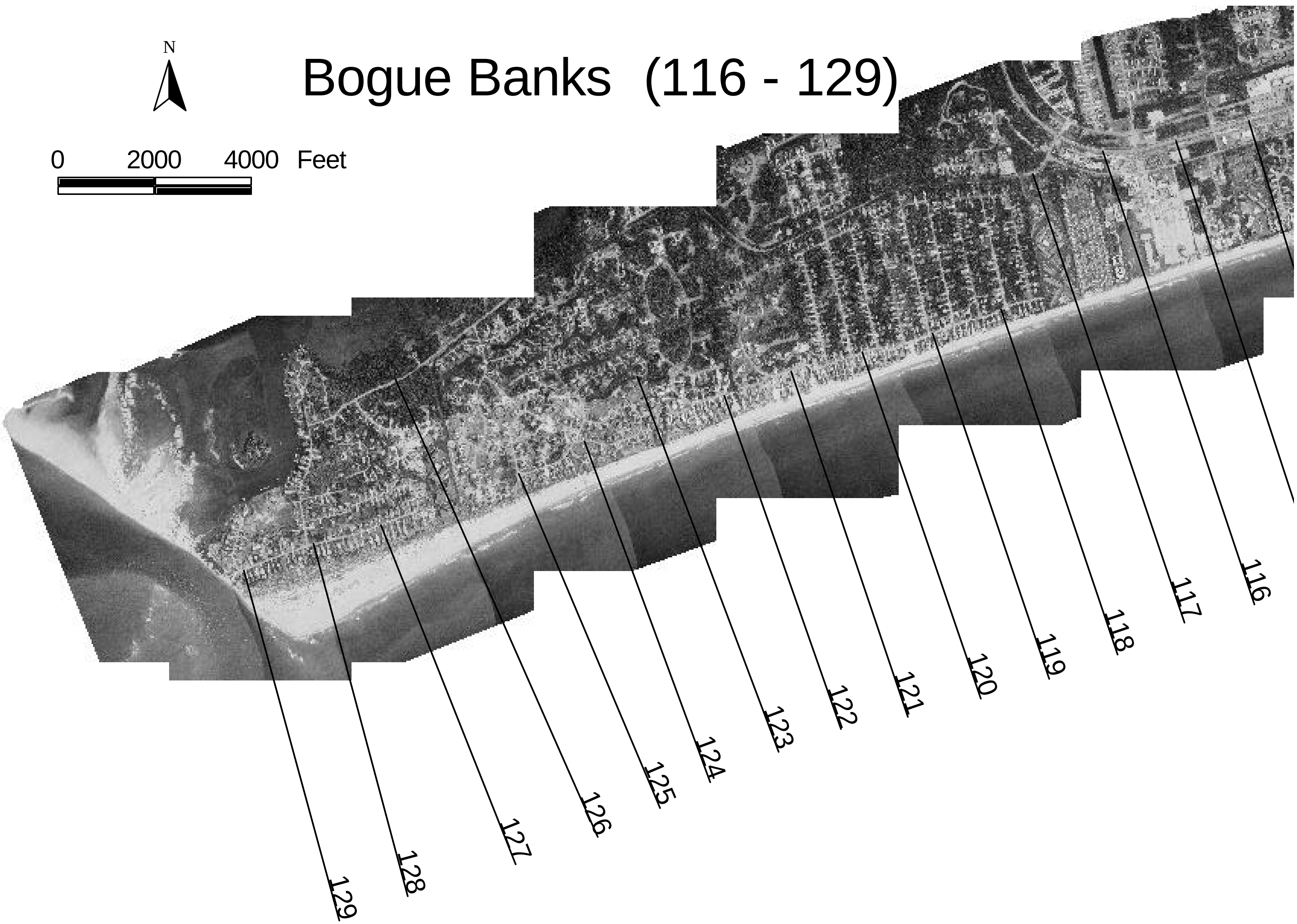

Figure 11h. Transect locations on Bogue Banks.

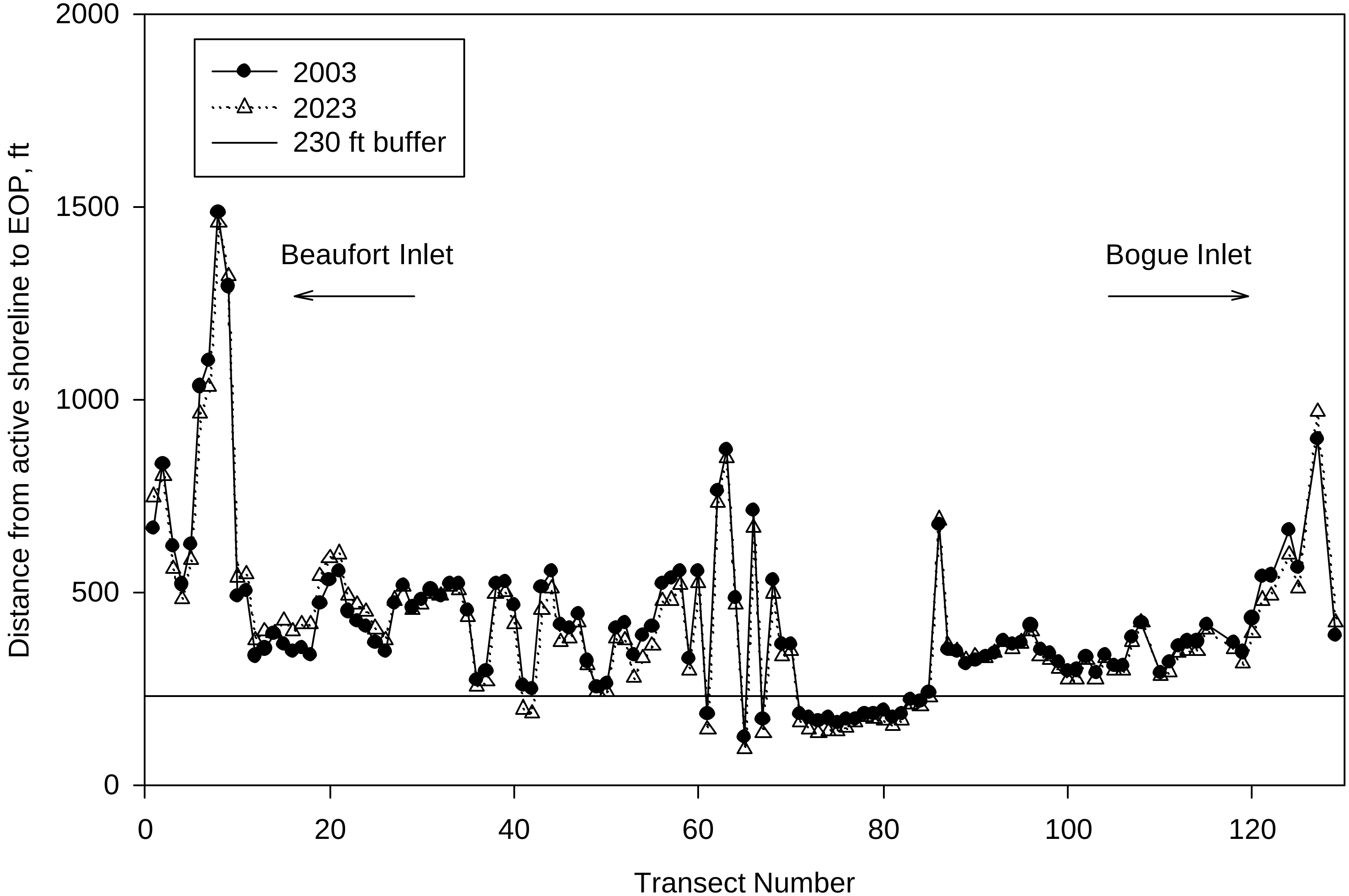

Figure 12. Distance from edge of pavement (EOP) to the active shoreline on Bogue Banks.

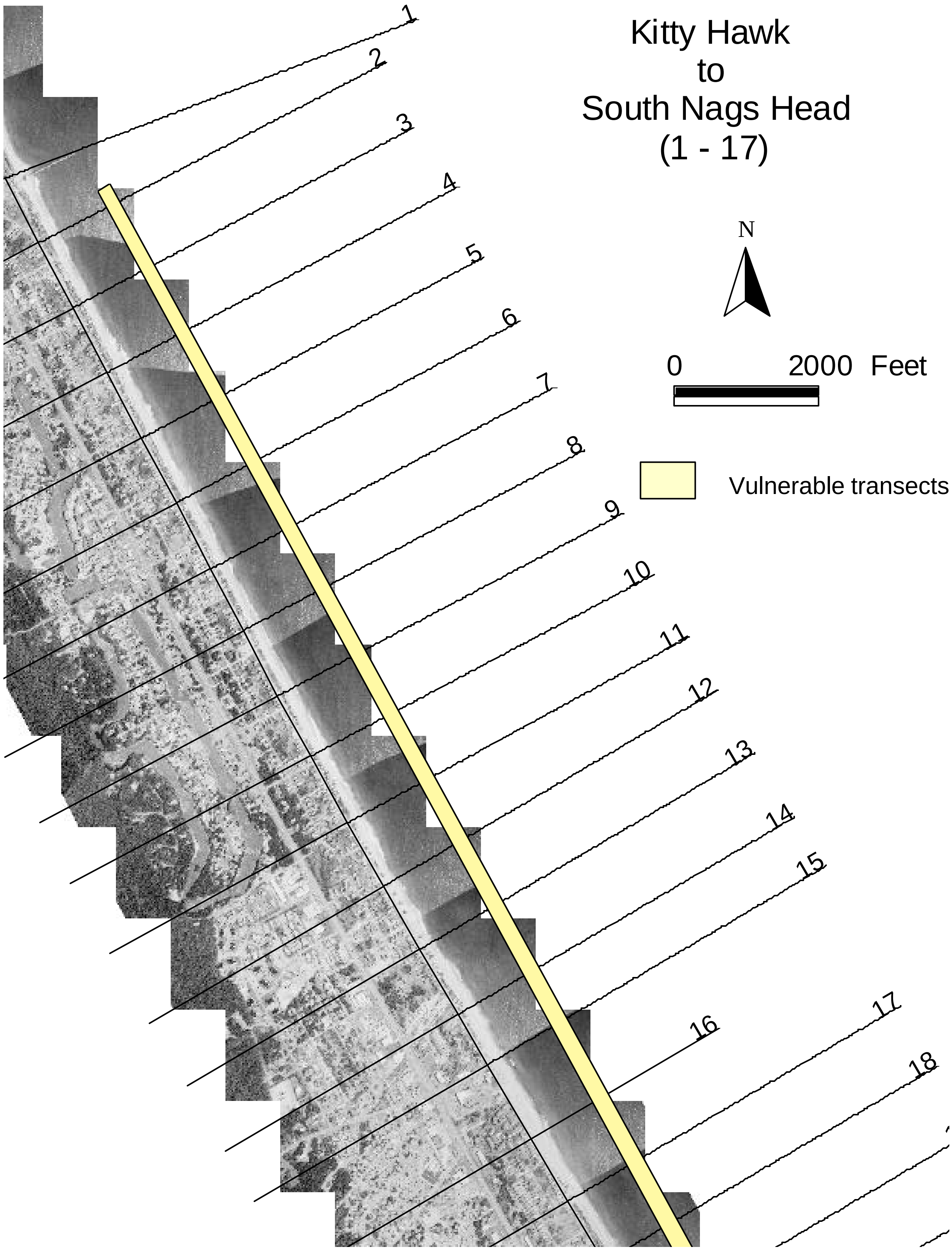

Figure 13a. Transect locations on the shoreline from Kitty Hawk to South Nags Head.

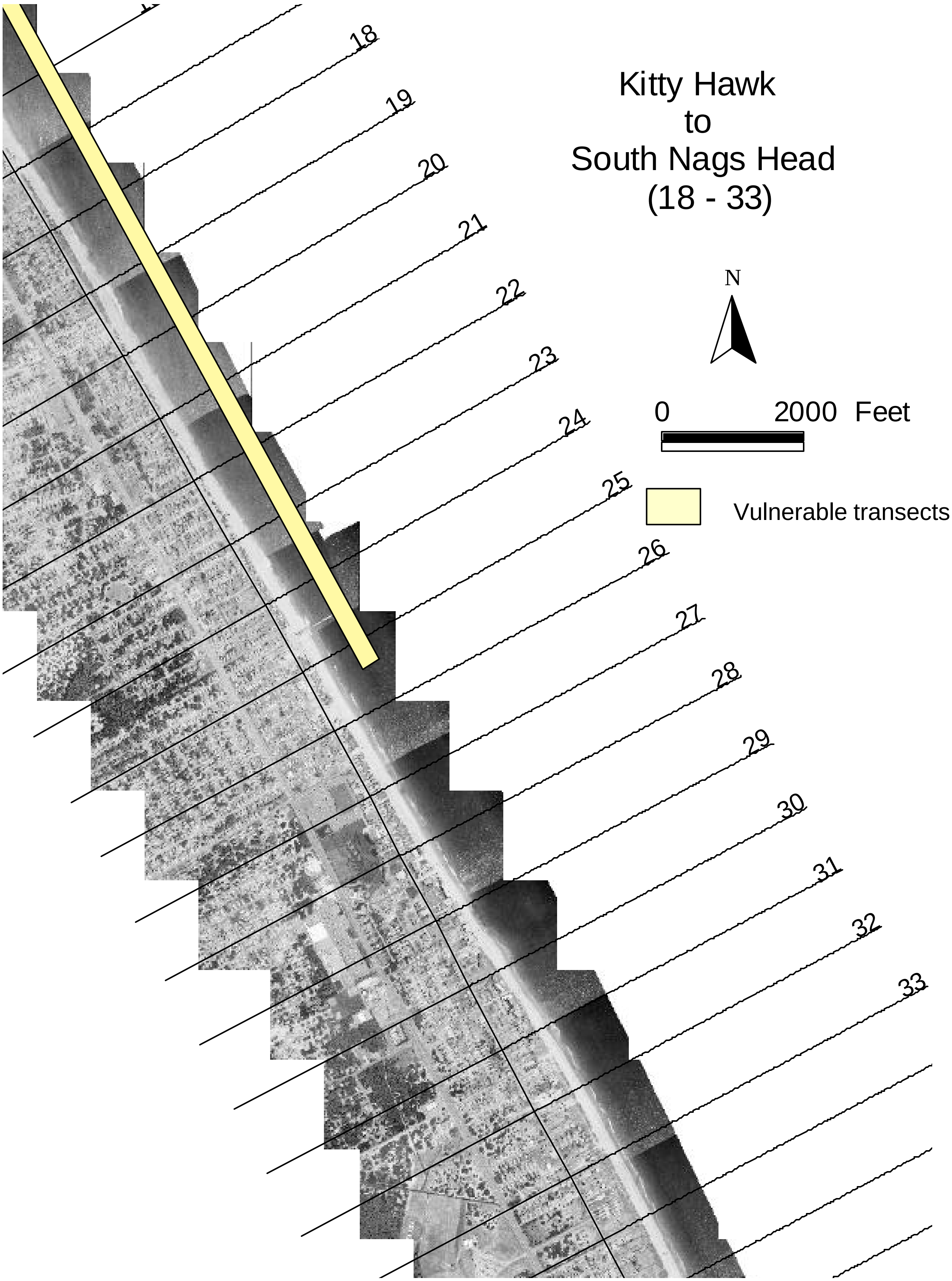

Figure 13b. Transect locations on the shoreline from Kitty Hawk to South Nags Head.

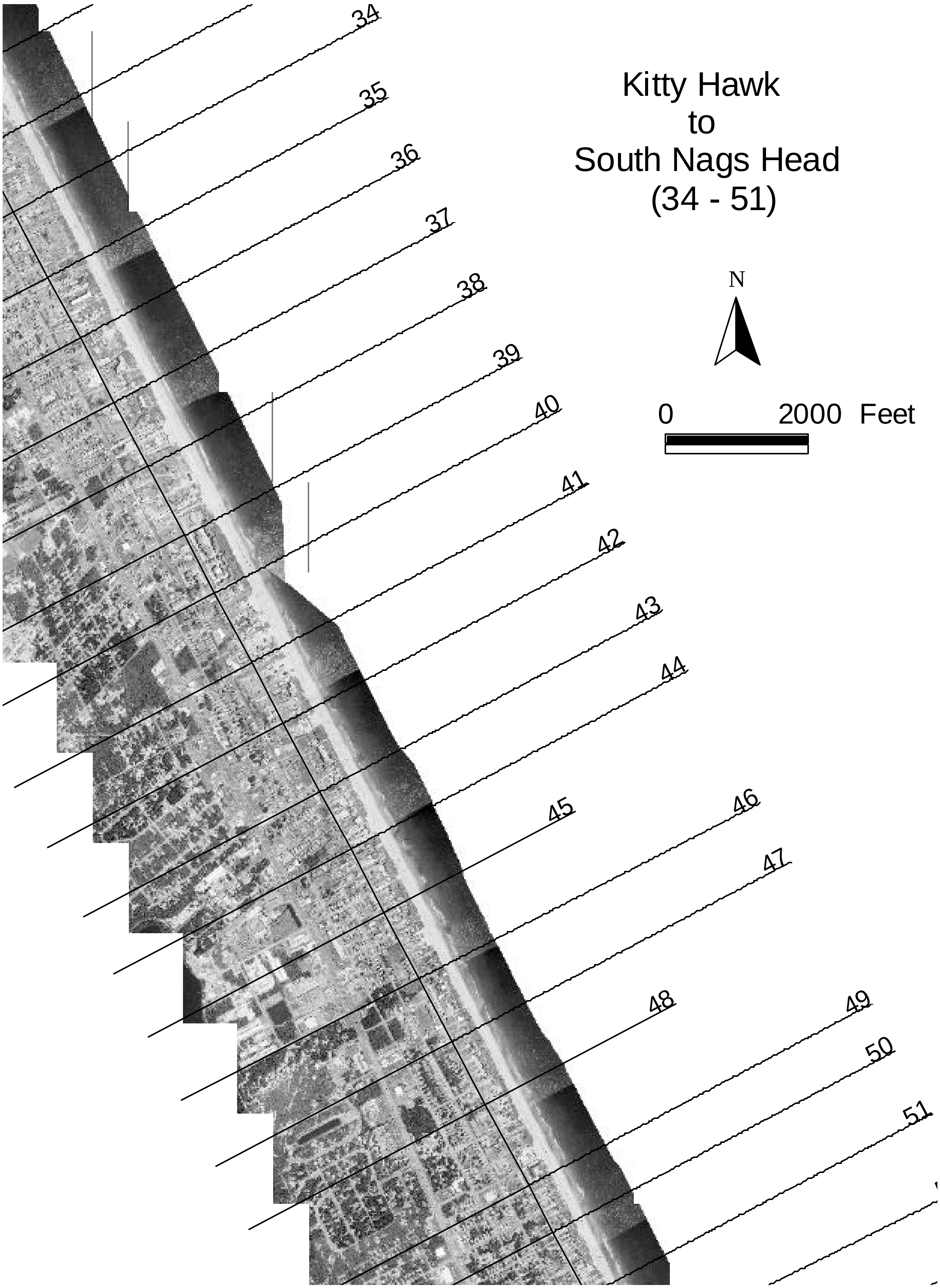

Figure 13c. Transect locations on the shoreline from Kitty Hawk to South Nags Head.

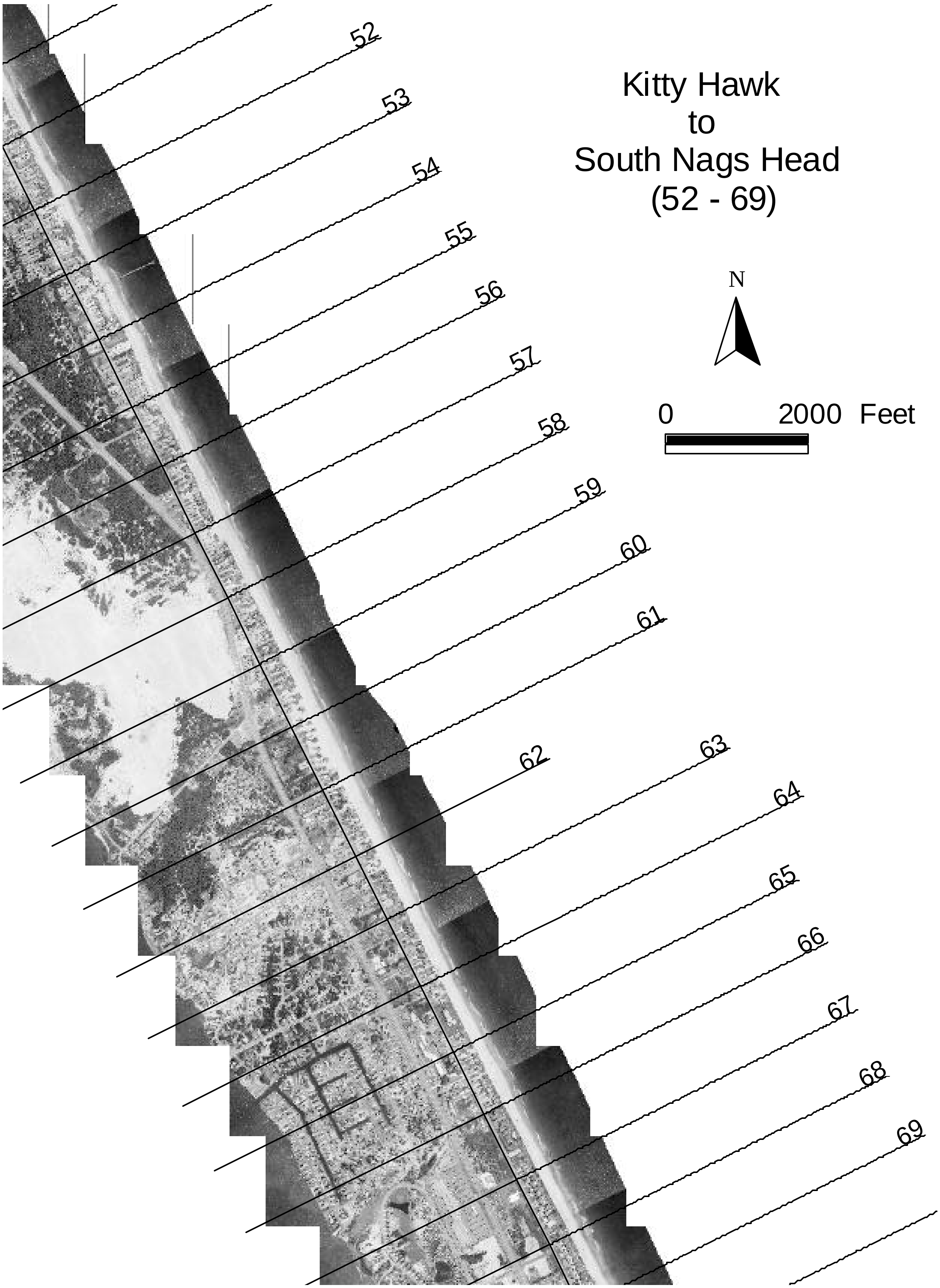

Figure 13d. Transect locations on the shoreline from Kitty Hawk to South Nags Head.

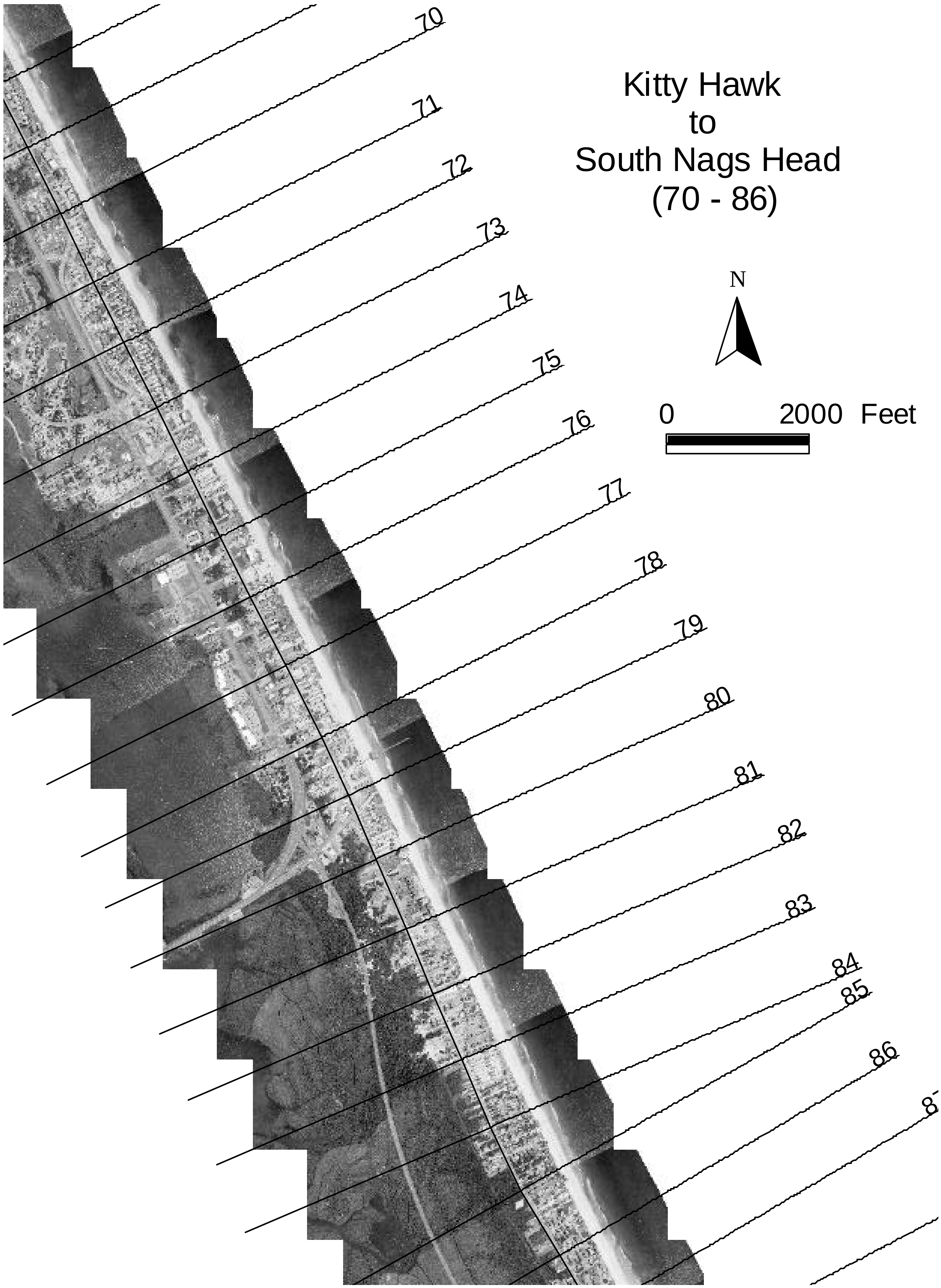

Figure 13e. Transect locations on the shoreline from Kitty Hawk to South Nags Head.

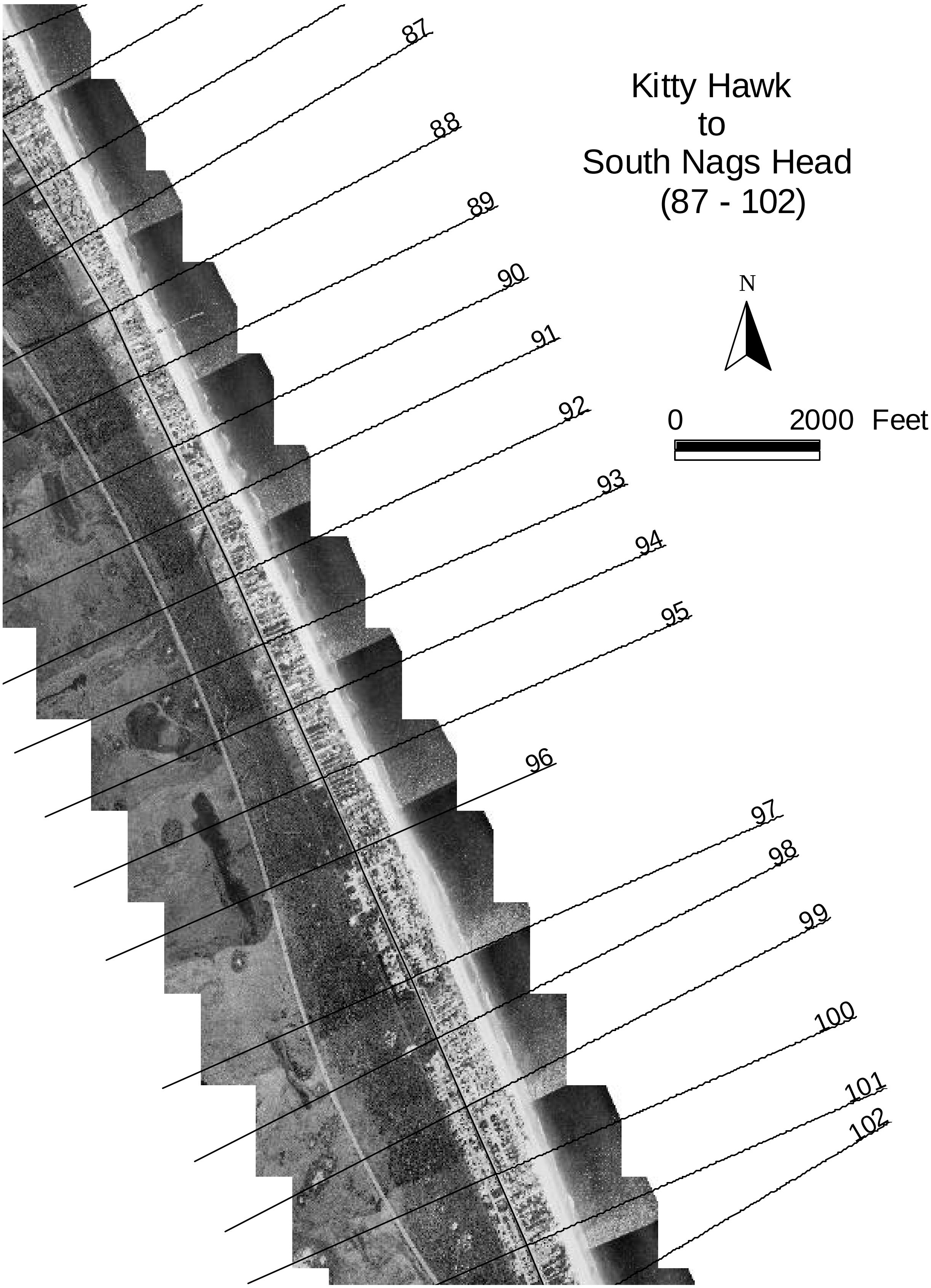

Figure 13f. Transect locations on the shoreline from Kitty Hawk to South Nags Head.

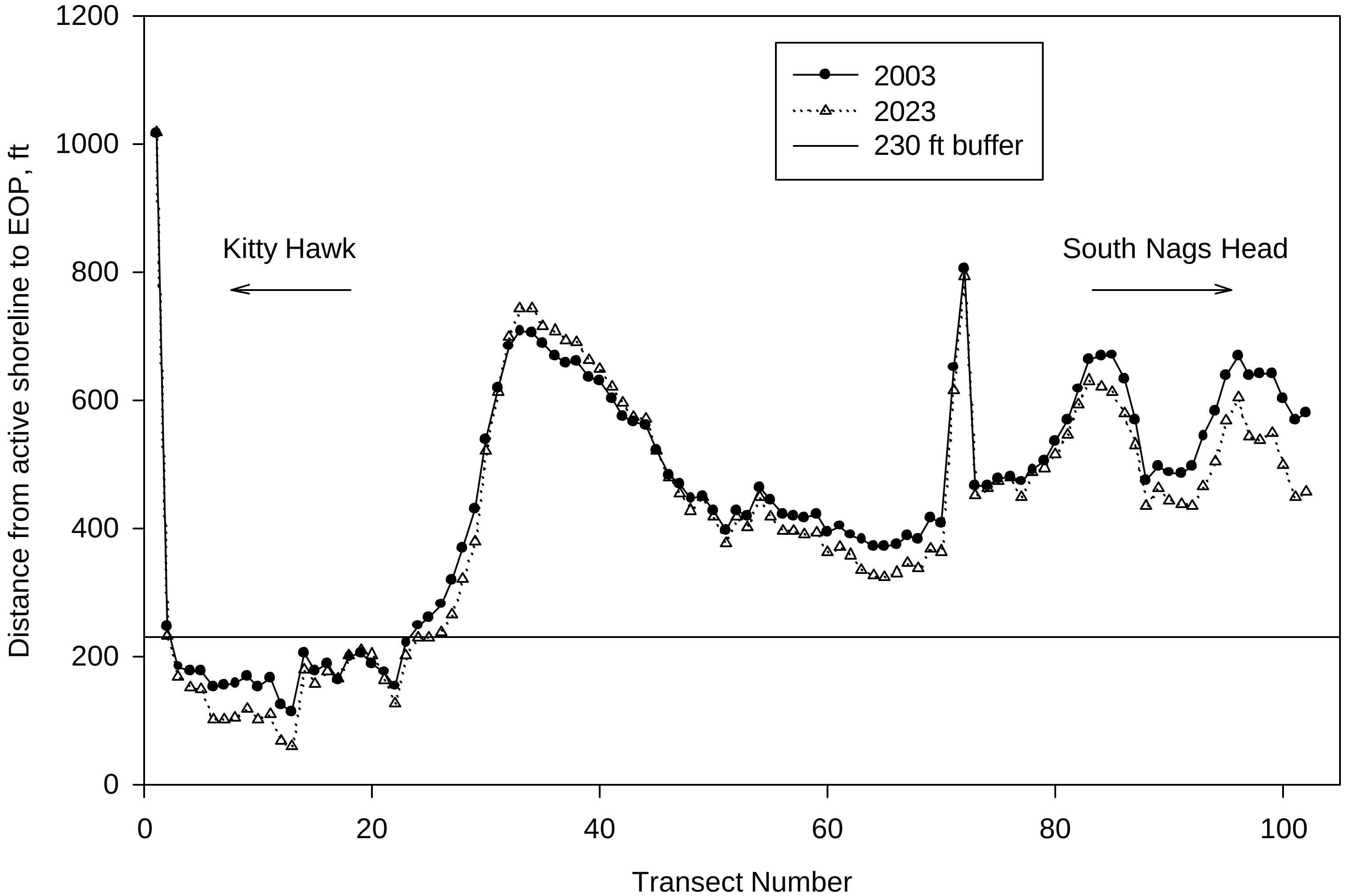

Figure 14. Distance from edge of pavement (EOP) to the active shoreline on the shoreline from Kitty Hawk to South Nags Head.

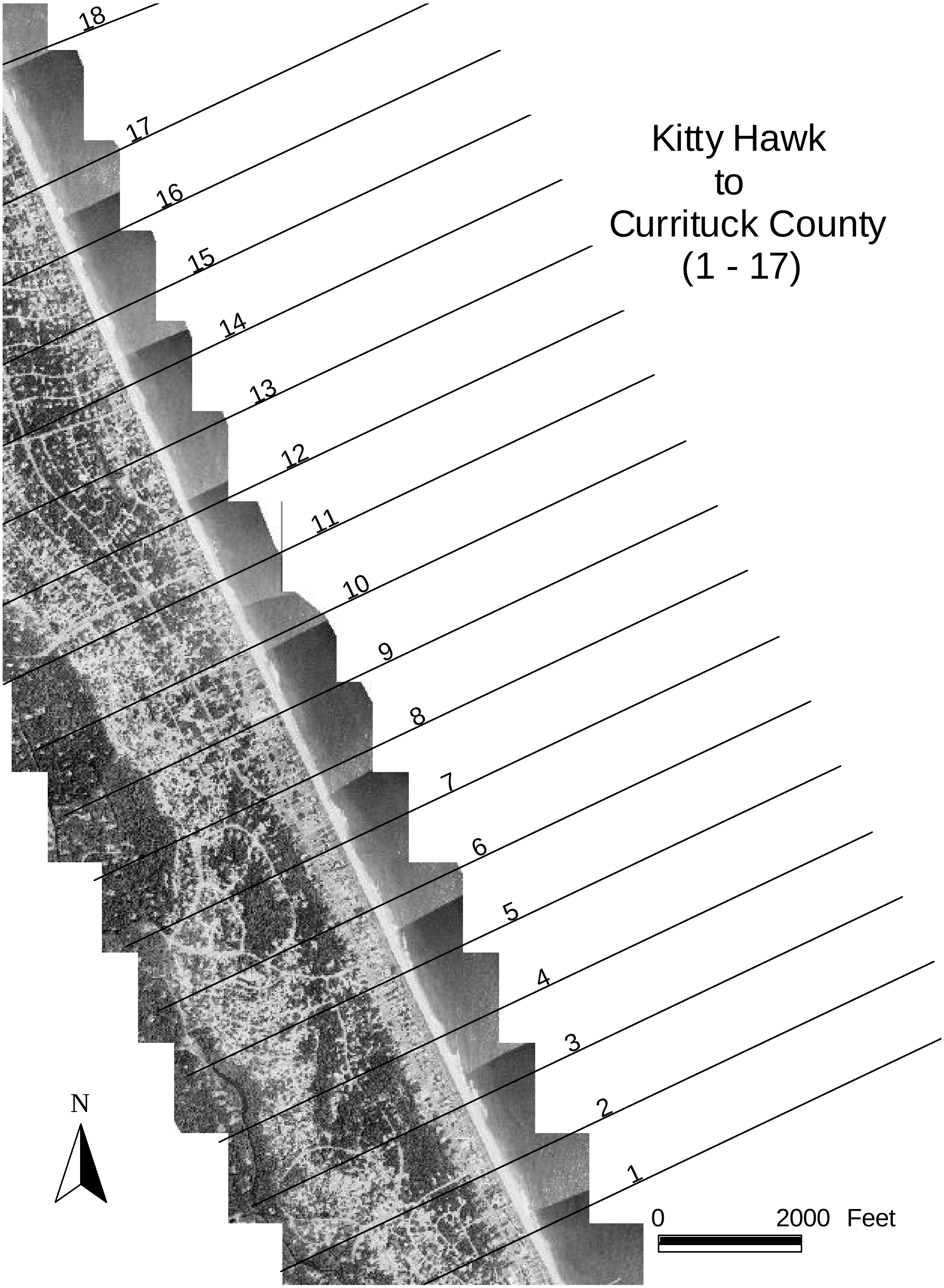

Figure 15a. Transect locations on the shoreline from Kitty Hawk to Currituck.

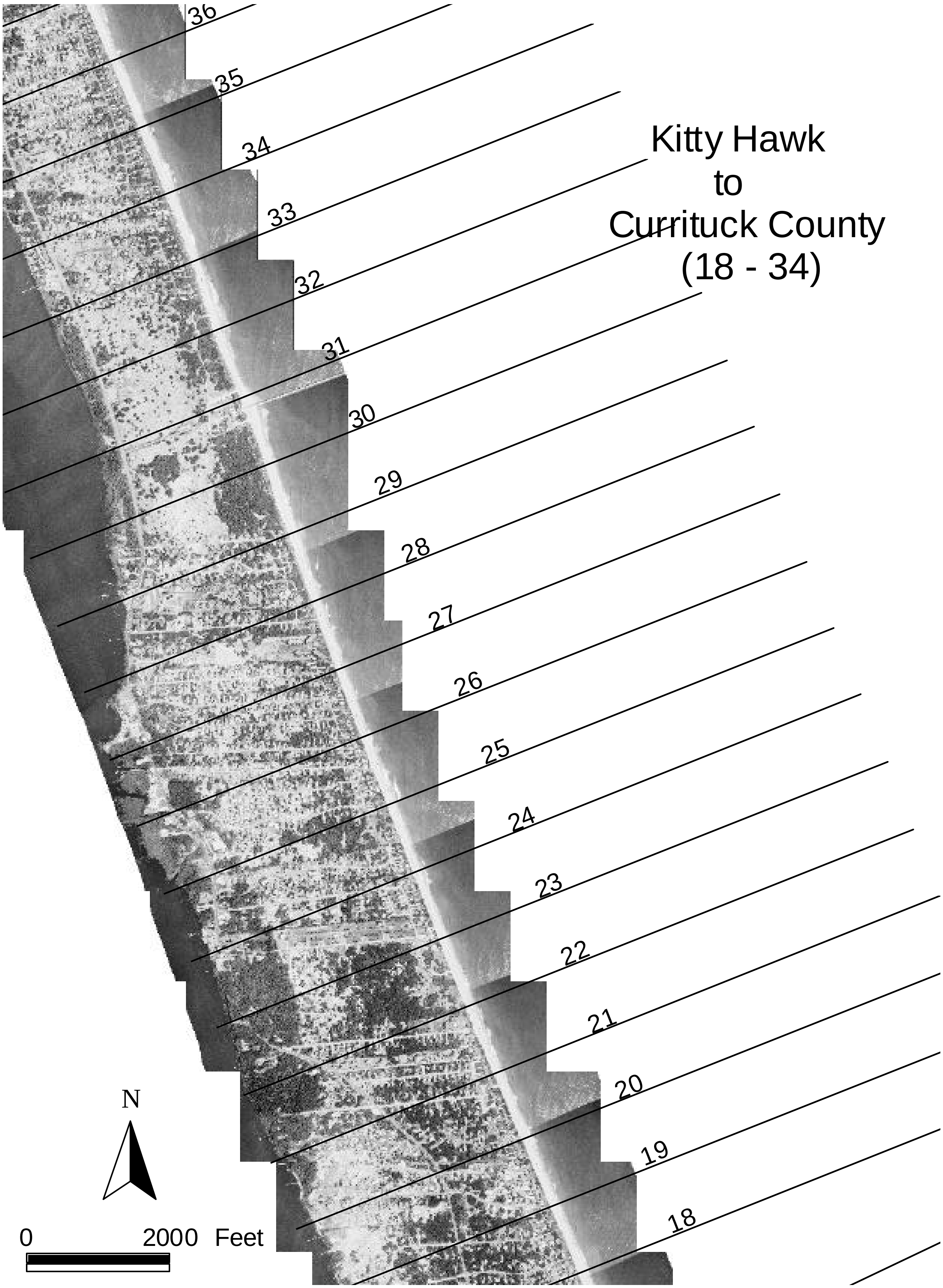

Figure 15b. Transect locations on the shoreline from Kitty Hawk to Currituck.

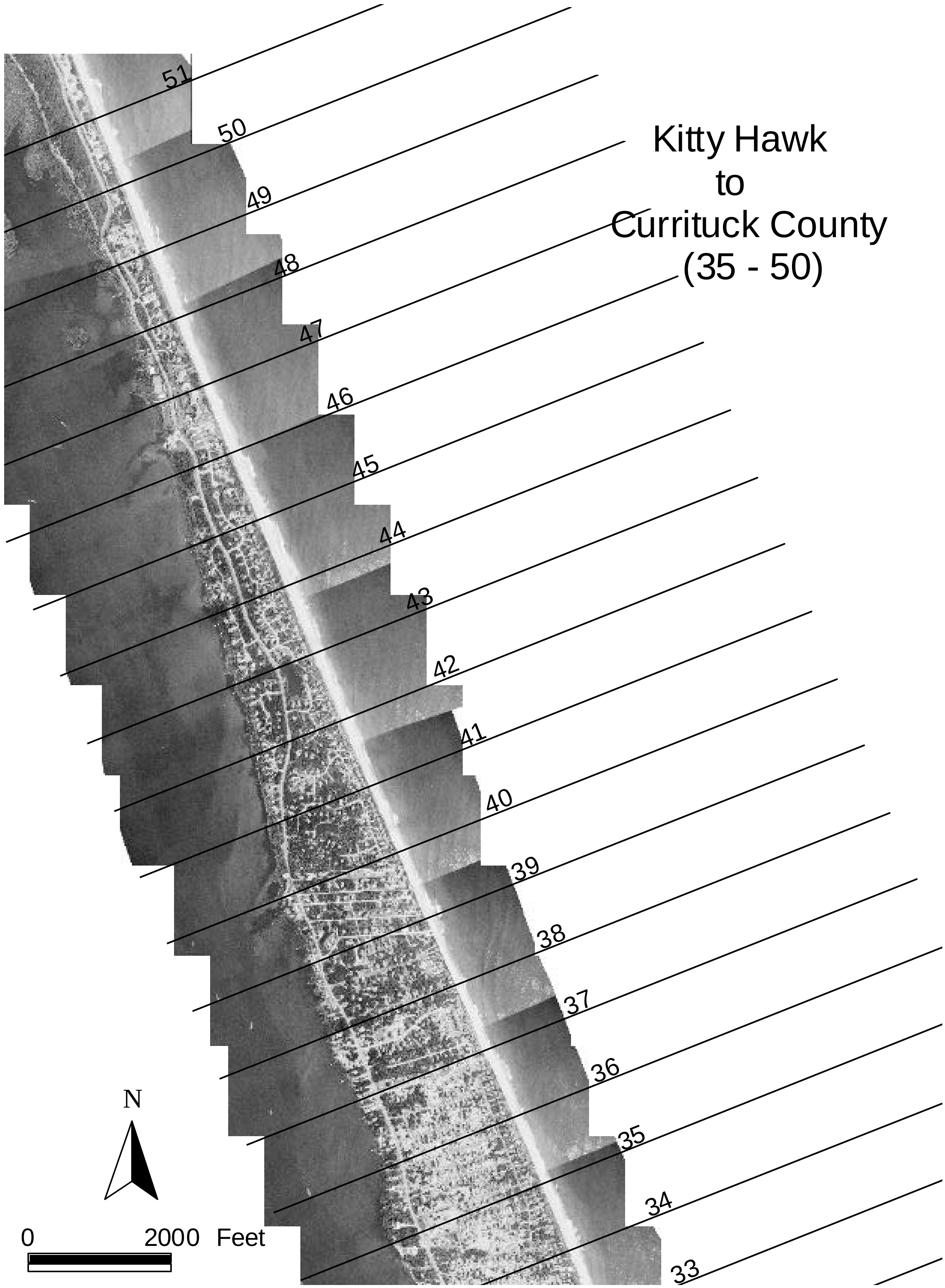

Figure 15c. Transect locations on the shoreline from Kitty Hawk to Currituck.

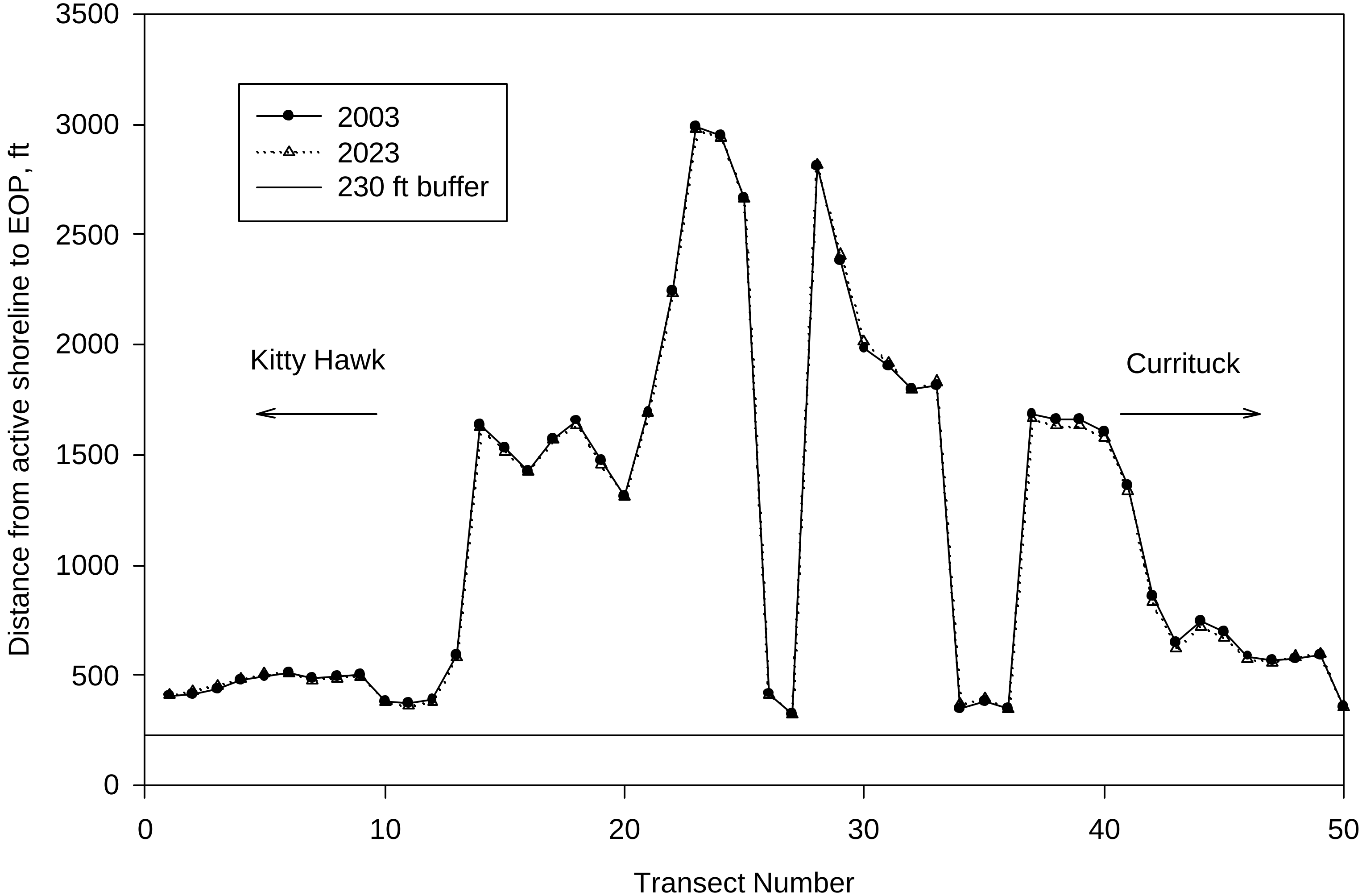

Figure 16. Distance from edge of pavement (EOP) to the active shoreline on the shoreline from Kitty Hawk to Currituck.

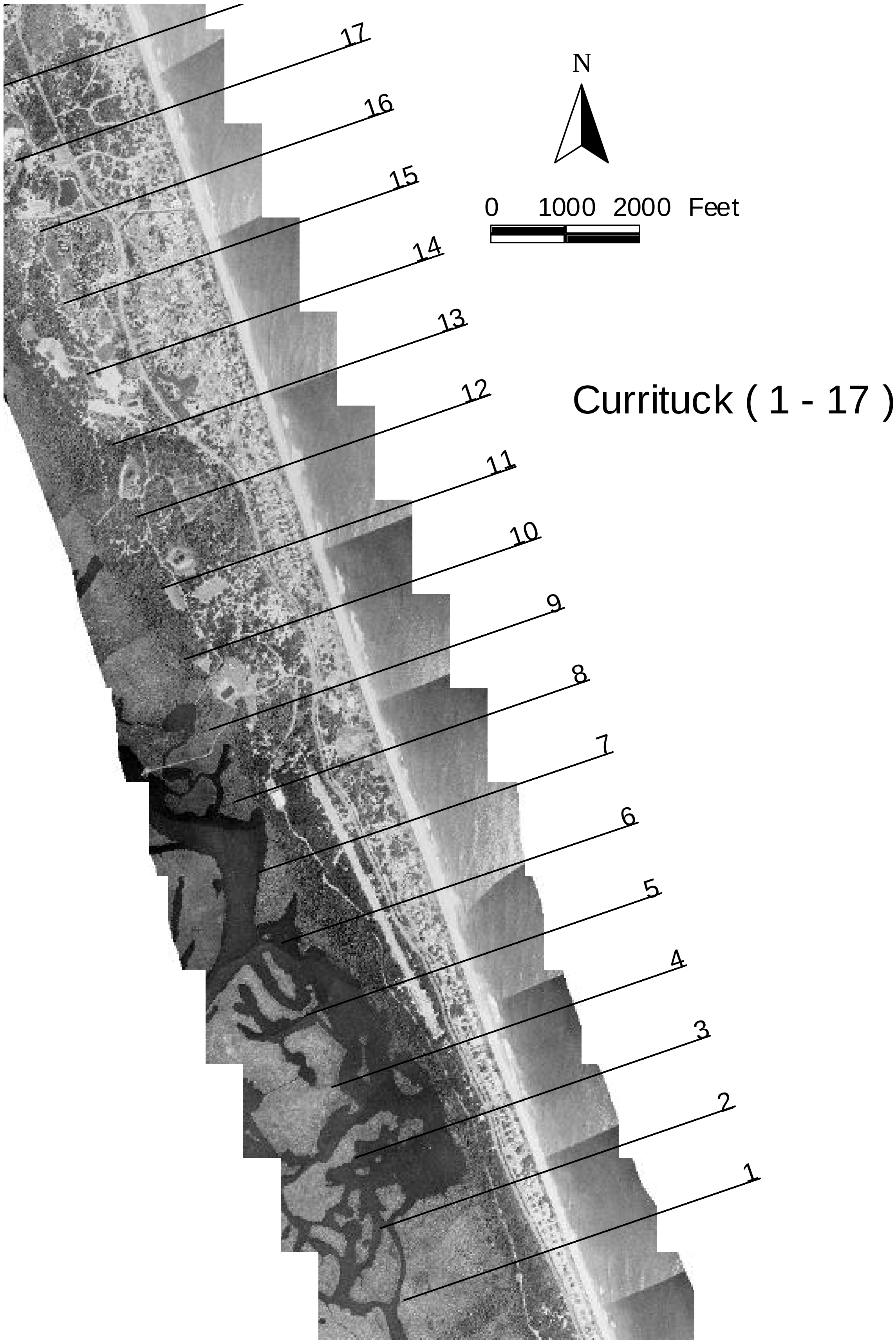

Figure 17a. Transect locations in Currituck County.

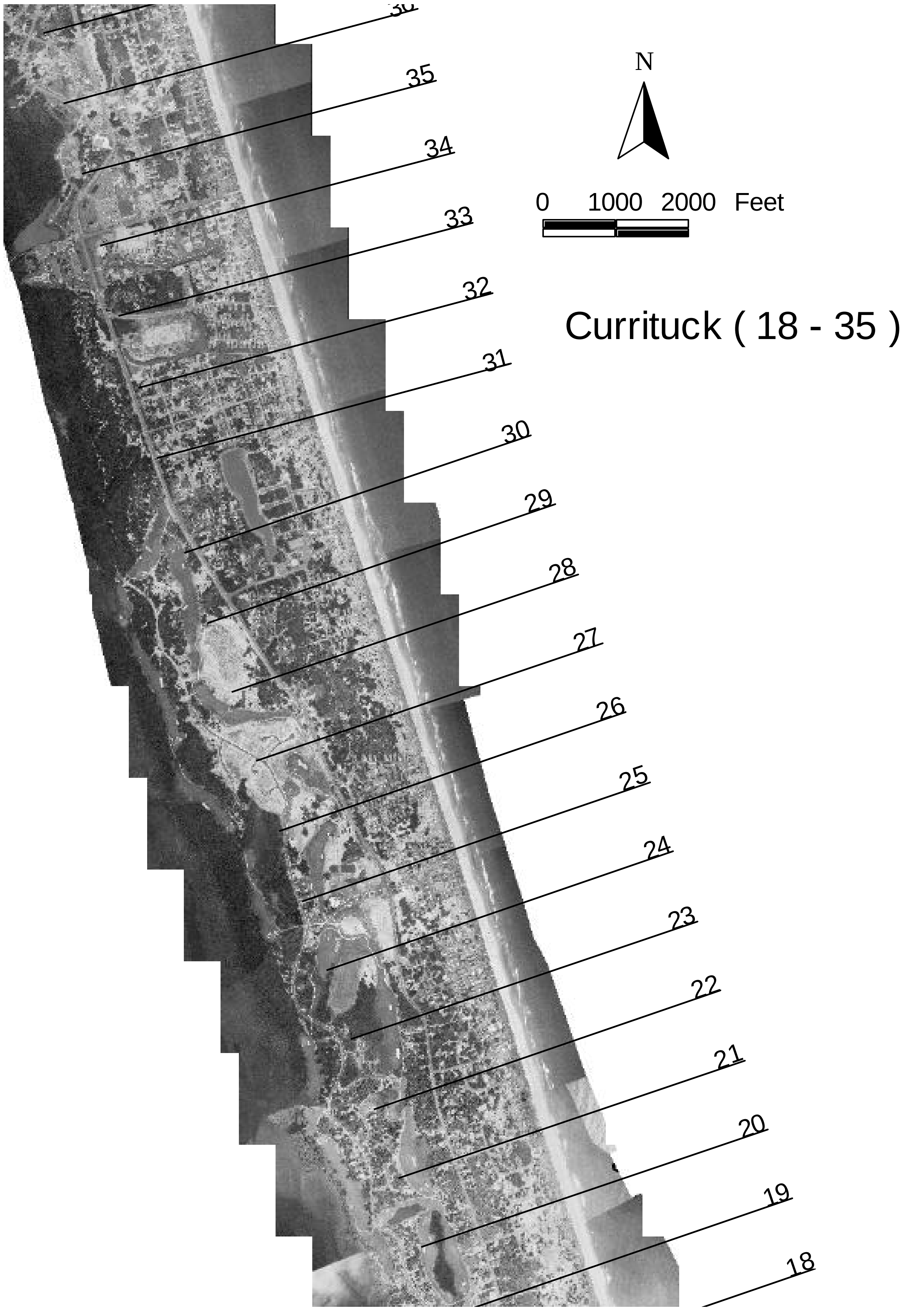

Figure 17b. Transect locations in Currituck County.

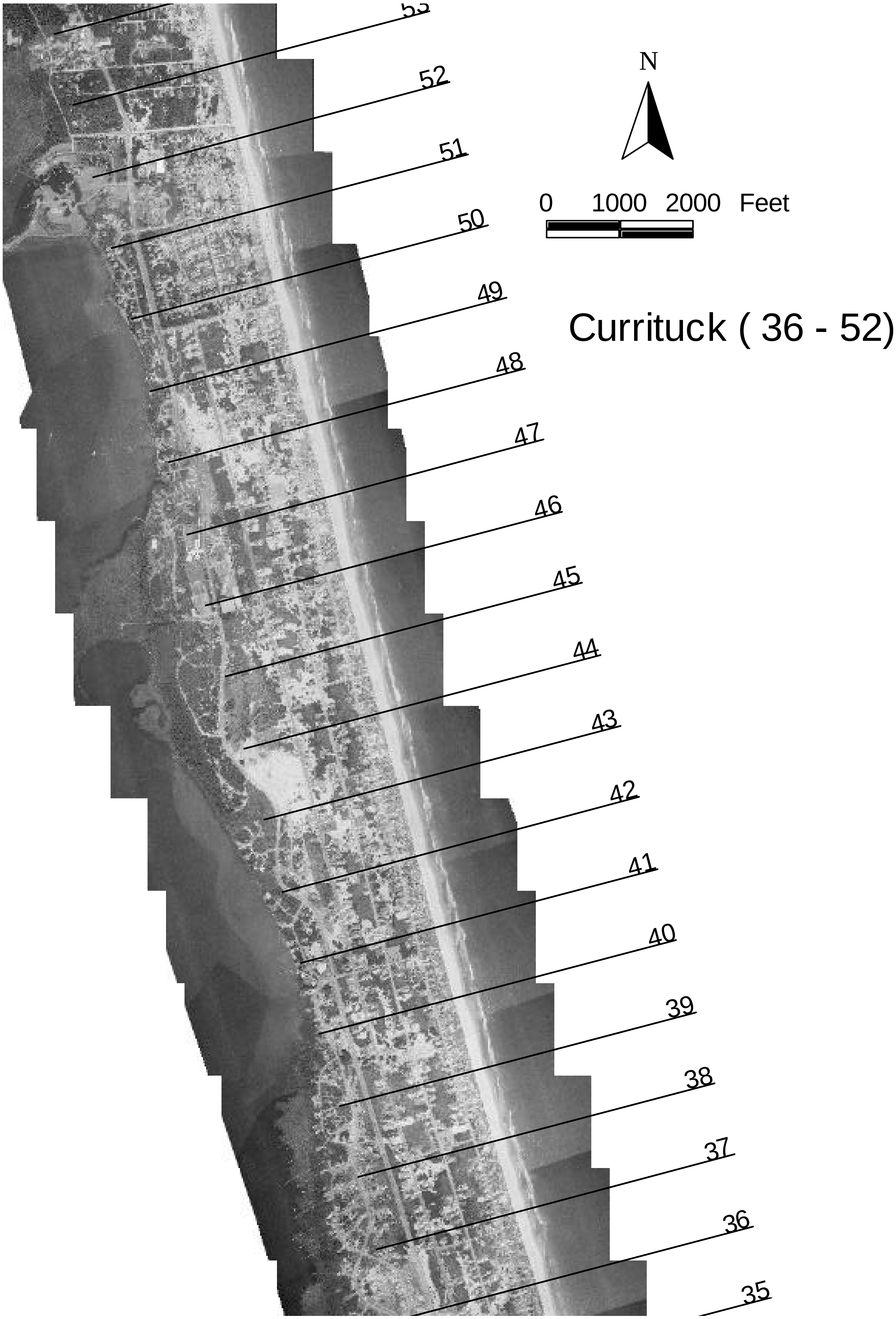

Figure 17c. Transect locations in Currituck County.

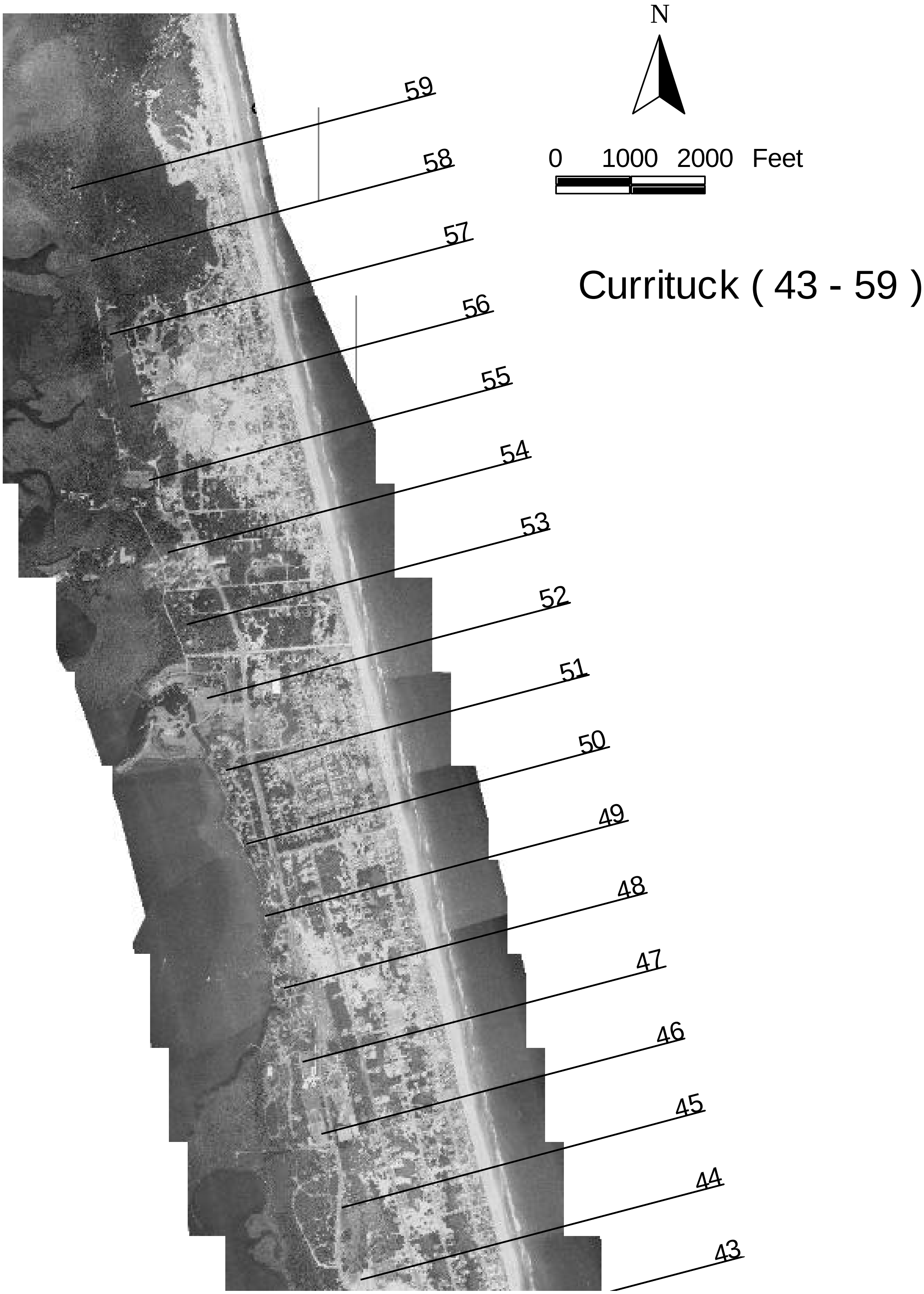

Figure 17d. Transect locations in Currituck County.

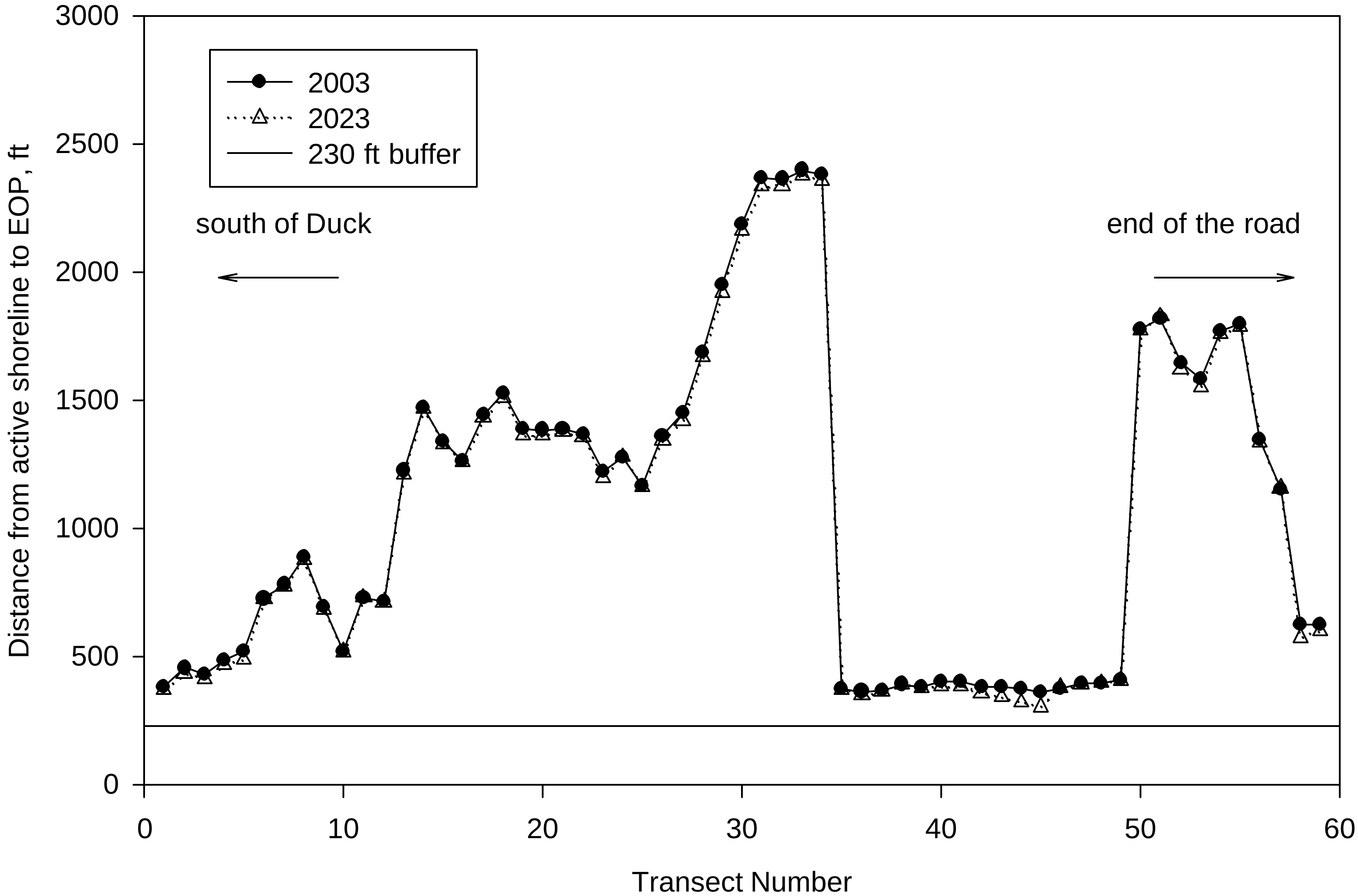

Figure 18. Distance from edge of pavement (EOP) to the active shoreline in Currituck County.

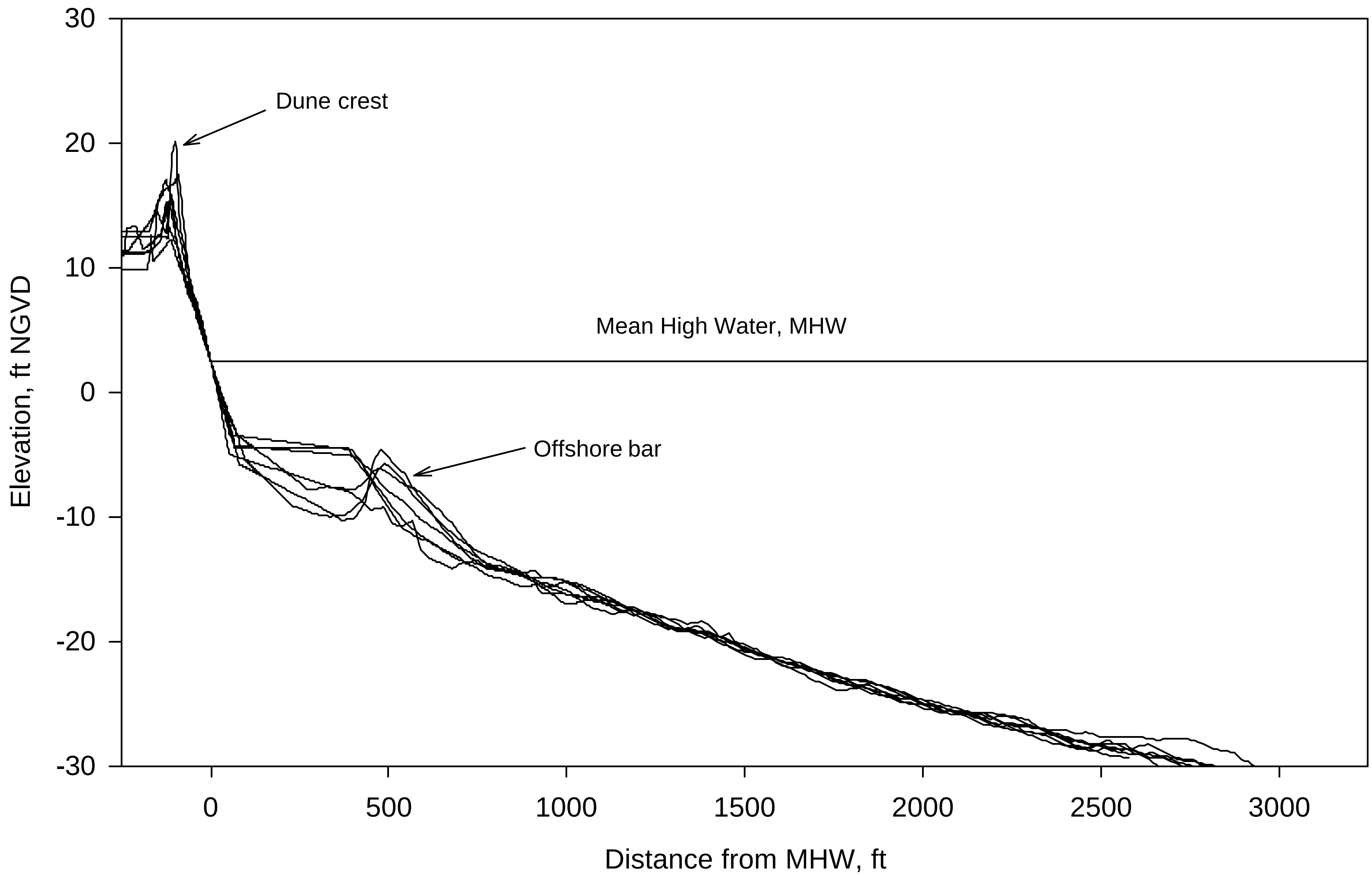

Figure 19. Cross-shore profile of transects NH2 through NH7 at the Kitty Hawk vulnerable area.

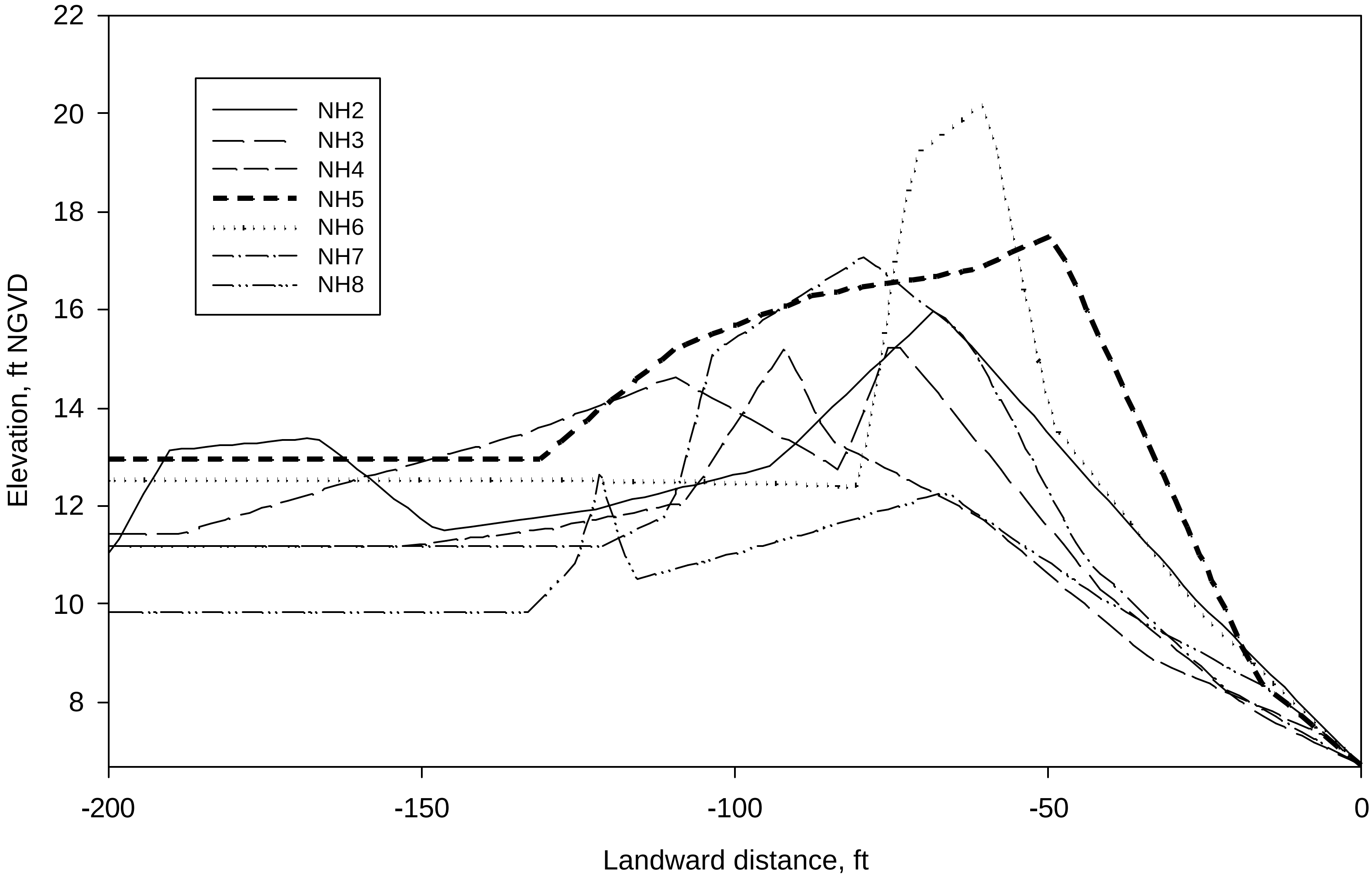

Figure 20. Subaerial profiles of transects NH2 through NH7 referenced from 6.7 ft elevation (the maximum recorded storm surge for Hurricane Isabel at the FRF).

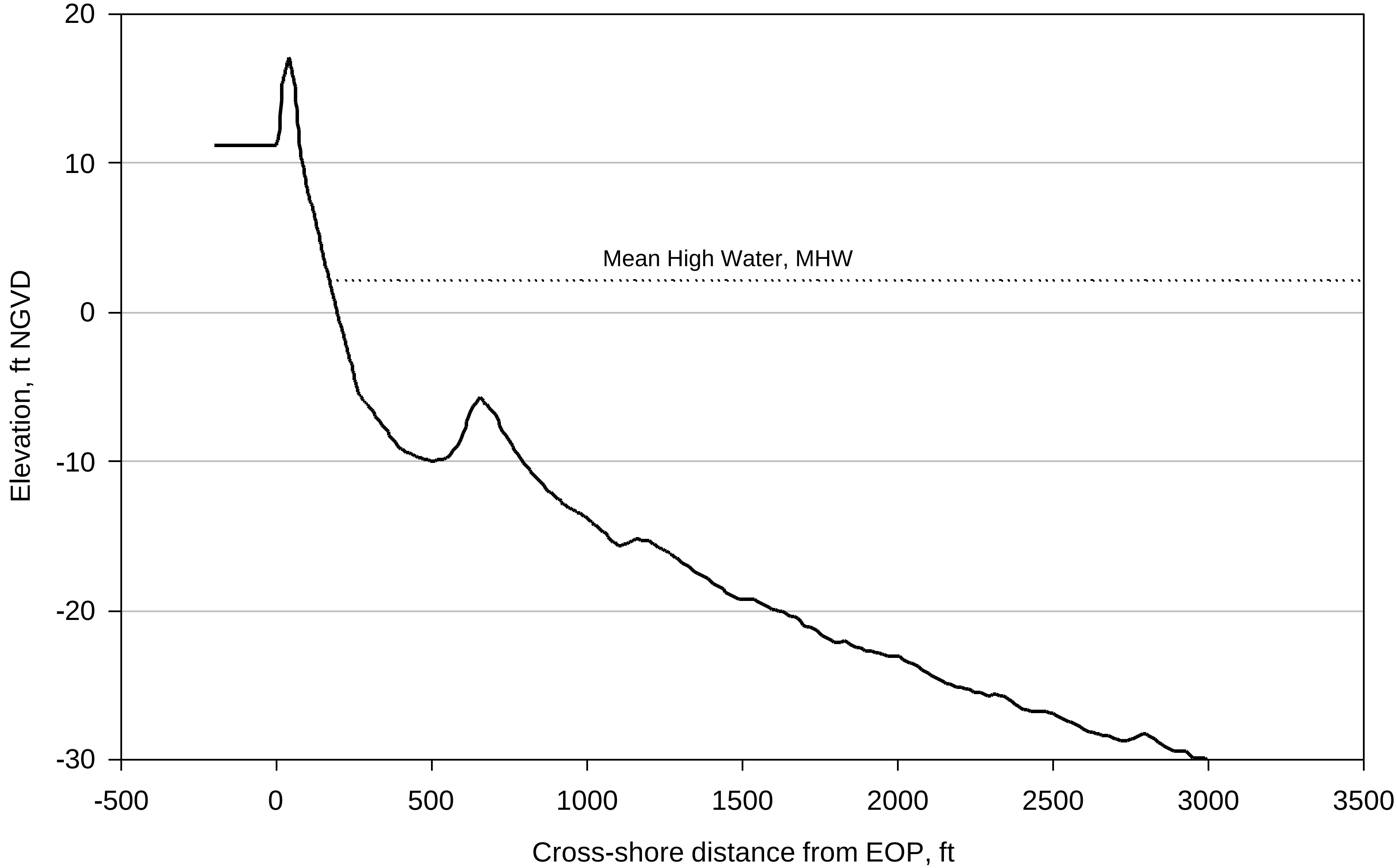

Figure 21. Cross-shore profile of transect NH7 at Kitty Hawk vulnerable area.

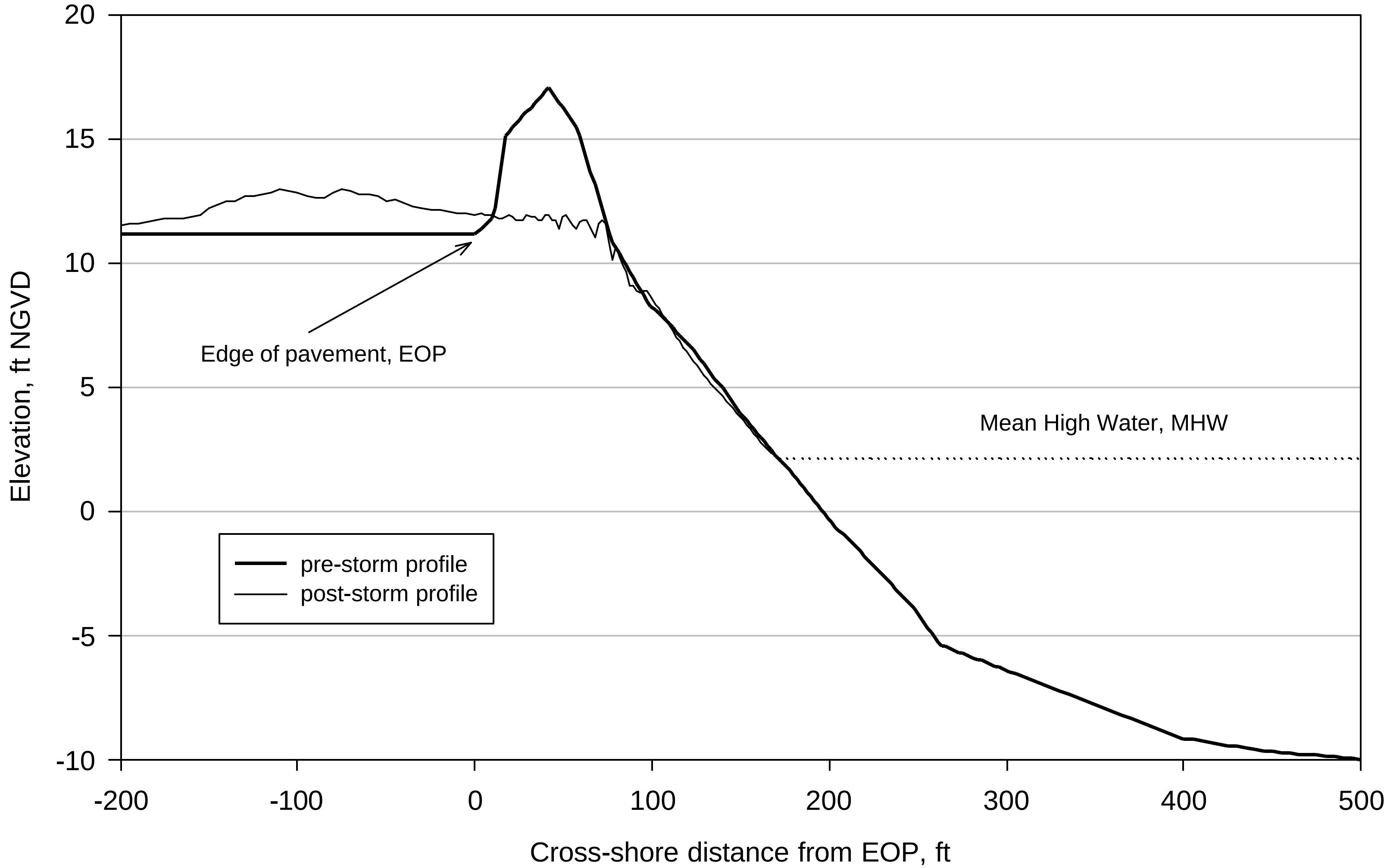

Figure 22. Cross-shore profile of transect NH7 at Kitty Hawk vulnerable area with SBEACH results for Hurricane Isabel.

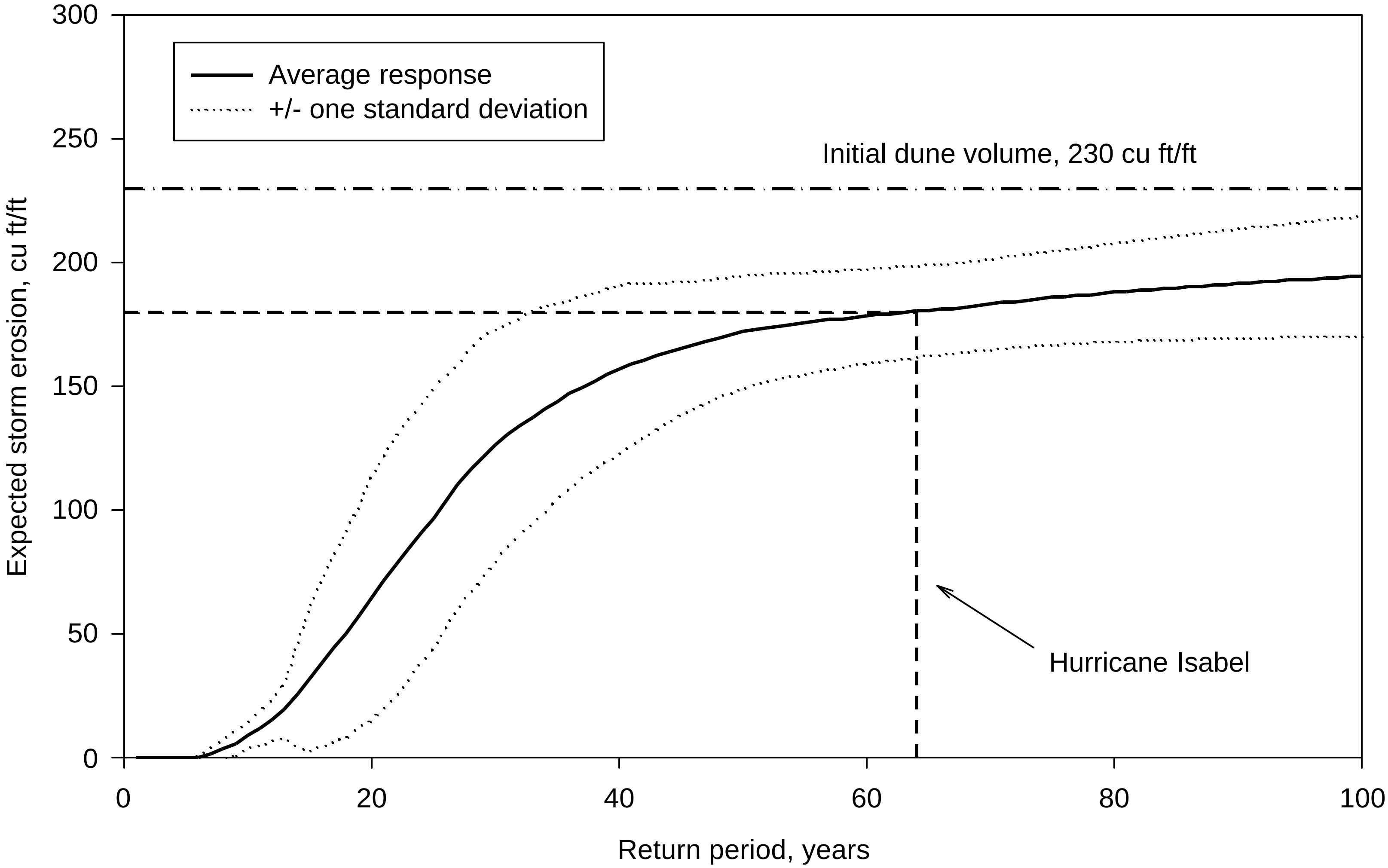

Figure 23a. Characterizing Hurricane Isabel with respect to expected storm erosion as a function of return period using EST results for transect NH2 at Kitty Hawk.

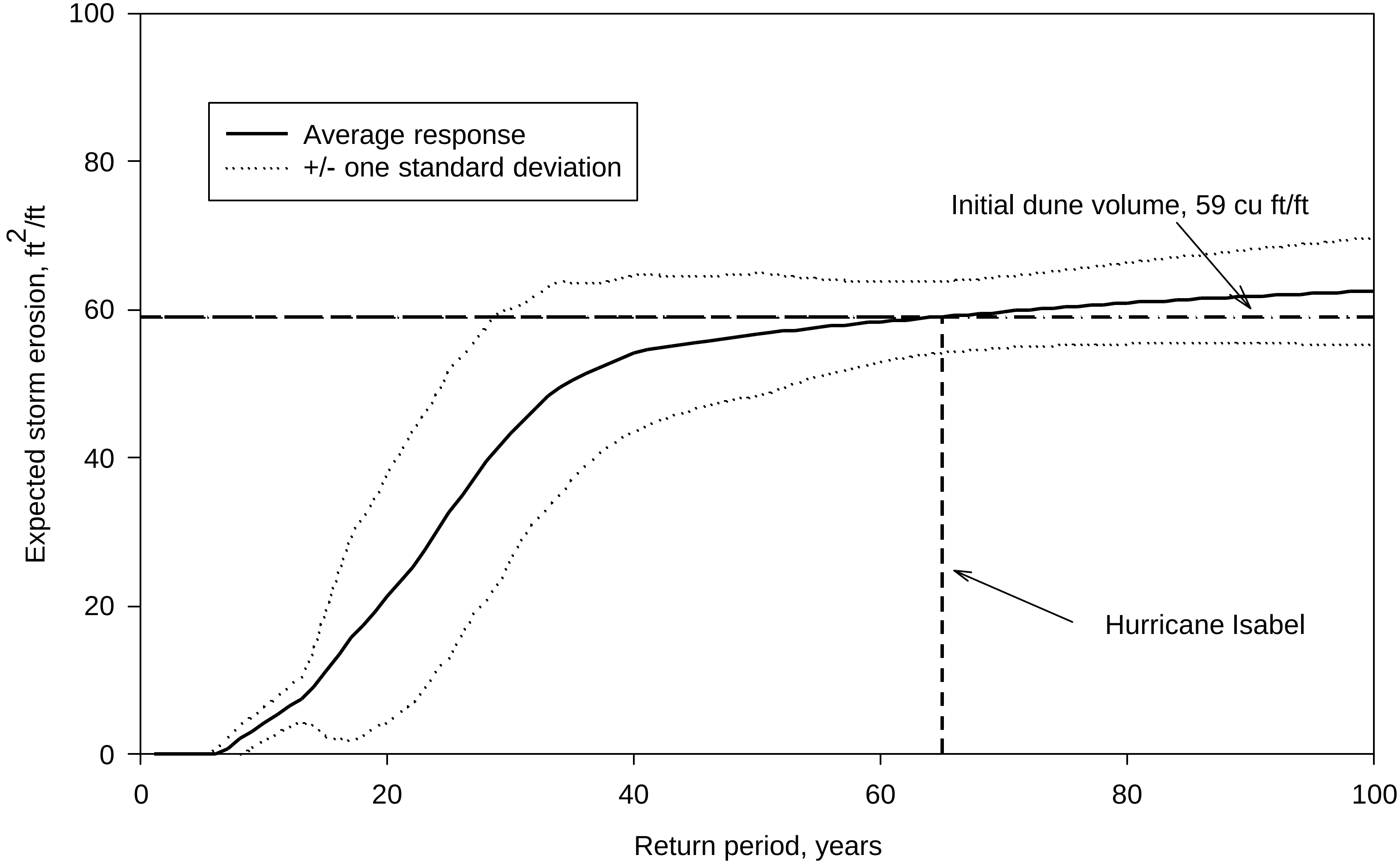

Figure 23b. Characterizing Hurricane Isabel with respect to expected storm erosion as a function of return period using EST results for transect NH3 at Kitty Hawk.

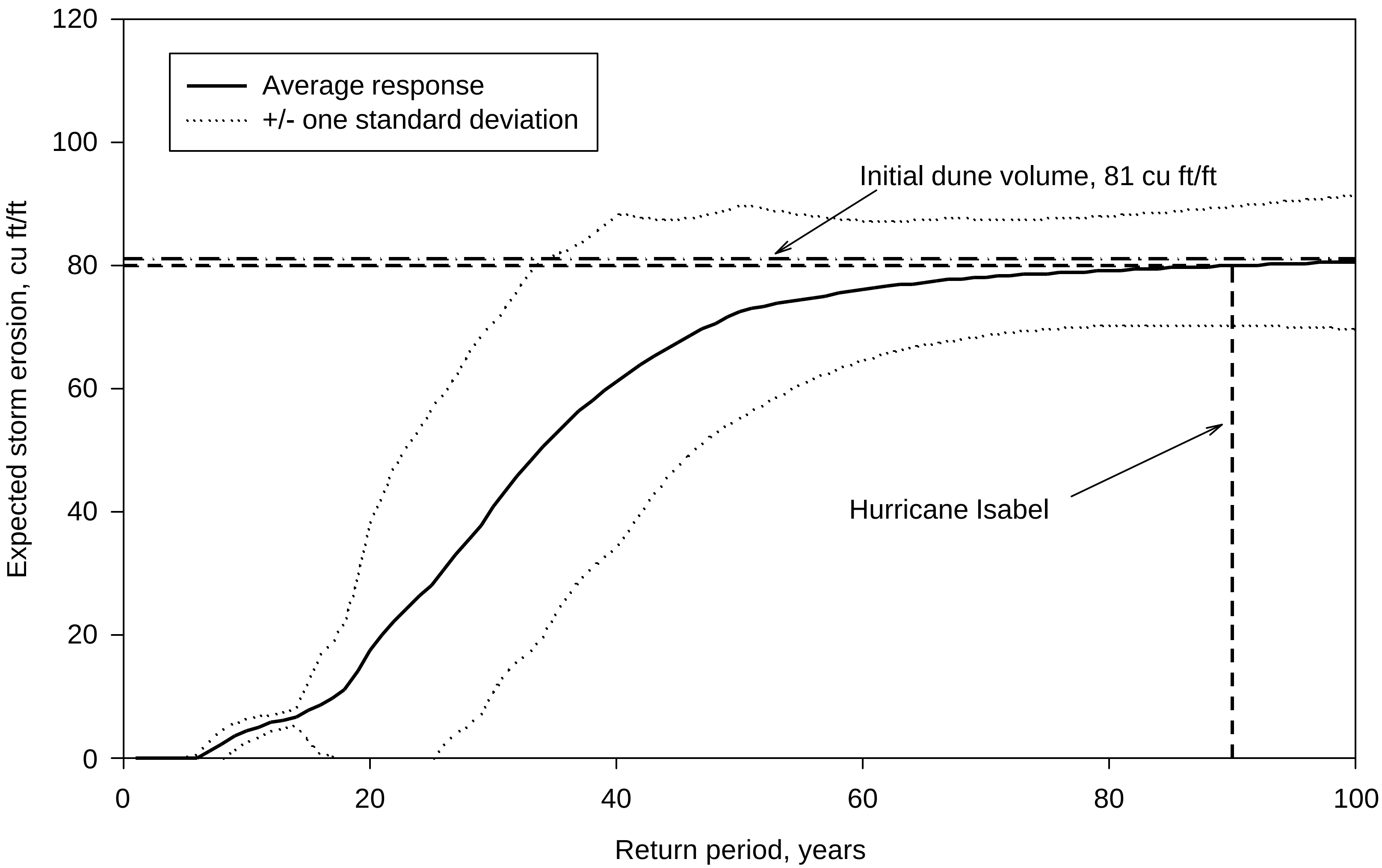

Figure 23c. Characterizing Hurricane Isabel with respect to expected storm erosion as a function of return period using EST results for transect NH4 at Kitty Hawk.

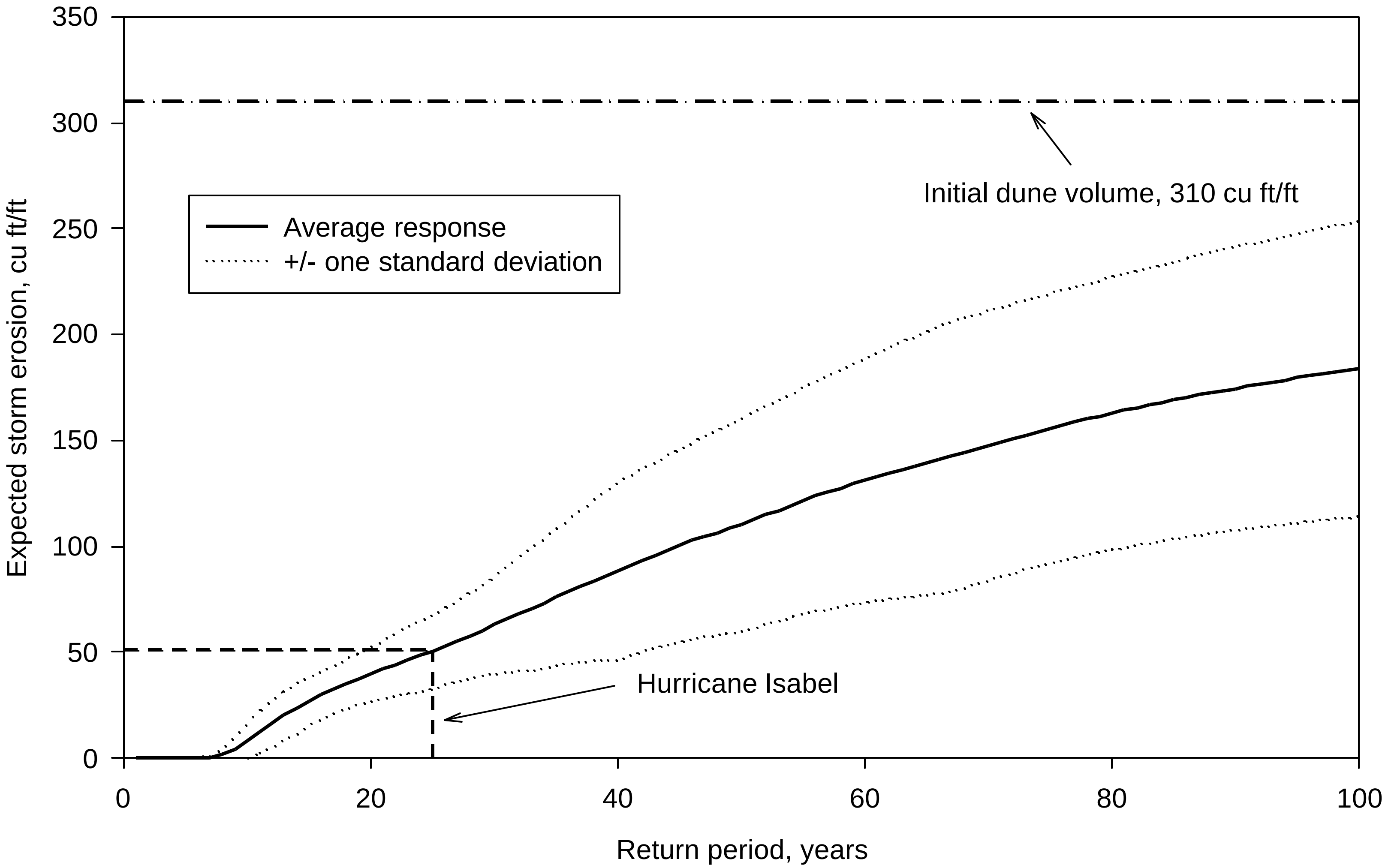

Figure 23d. Characterizing Hurricane Isabel with respect to expected storm erosion as a function of return period using EST results for transect NH5 at Kitty Hawk.

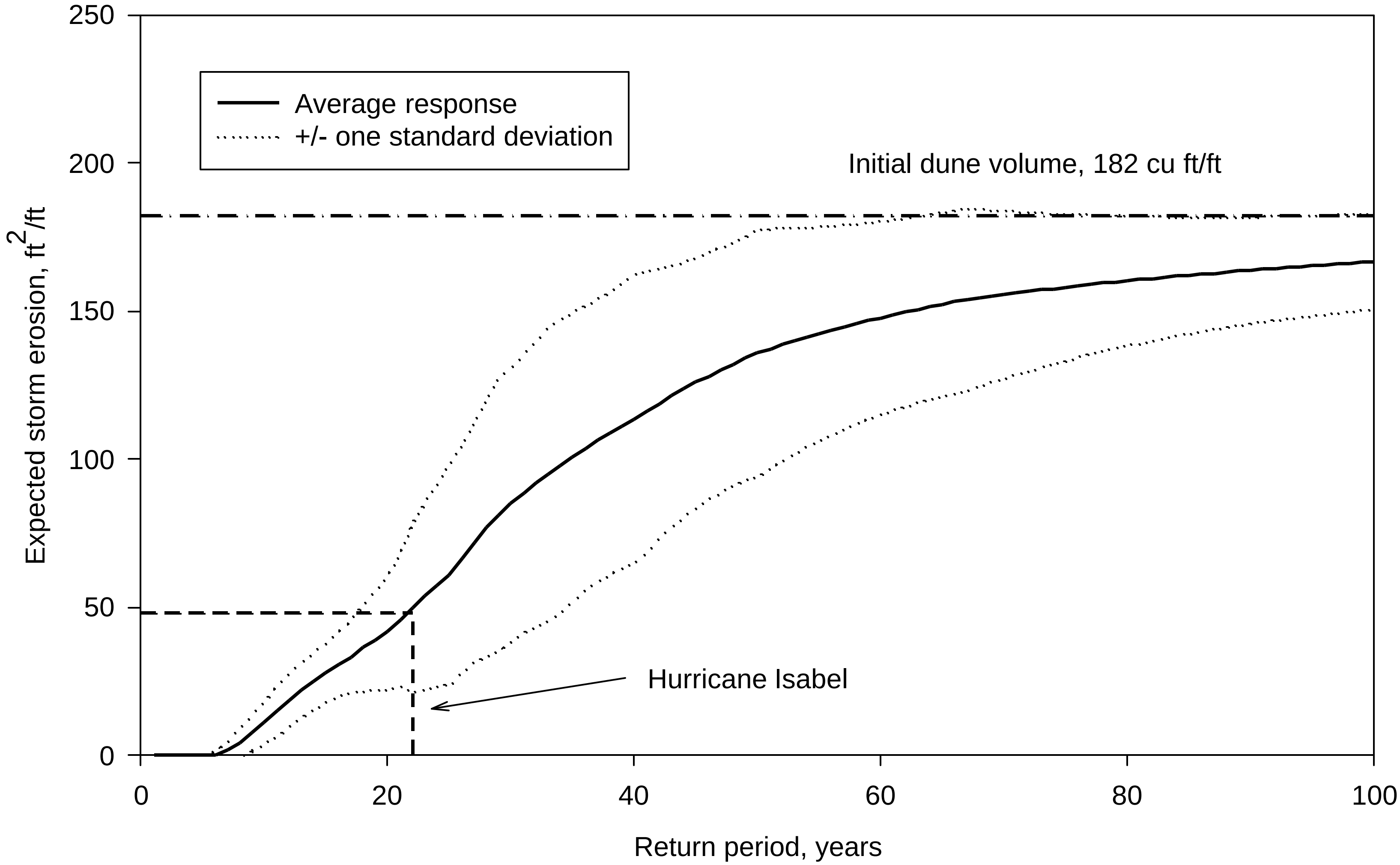

Figure 23e. Characterizing Hurricane Isabel with respect to expected storm erosion as a function of return period using EST results for transect NH6 at Kitty Hawk.

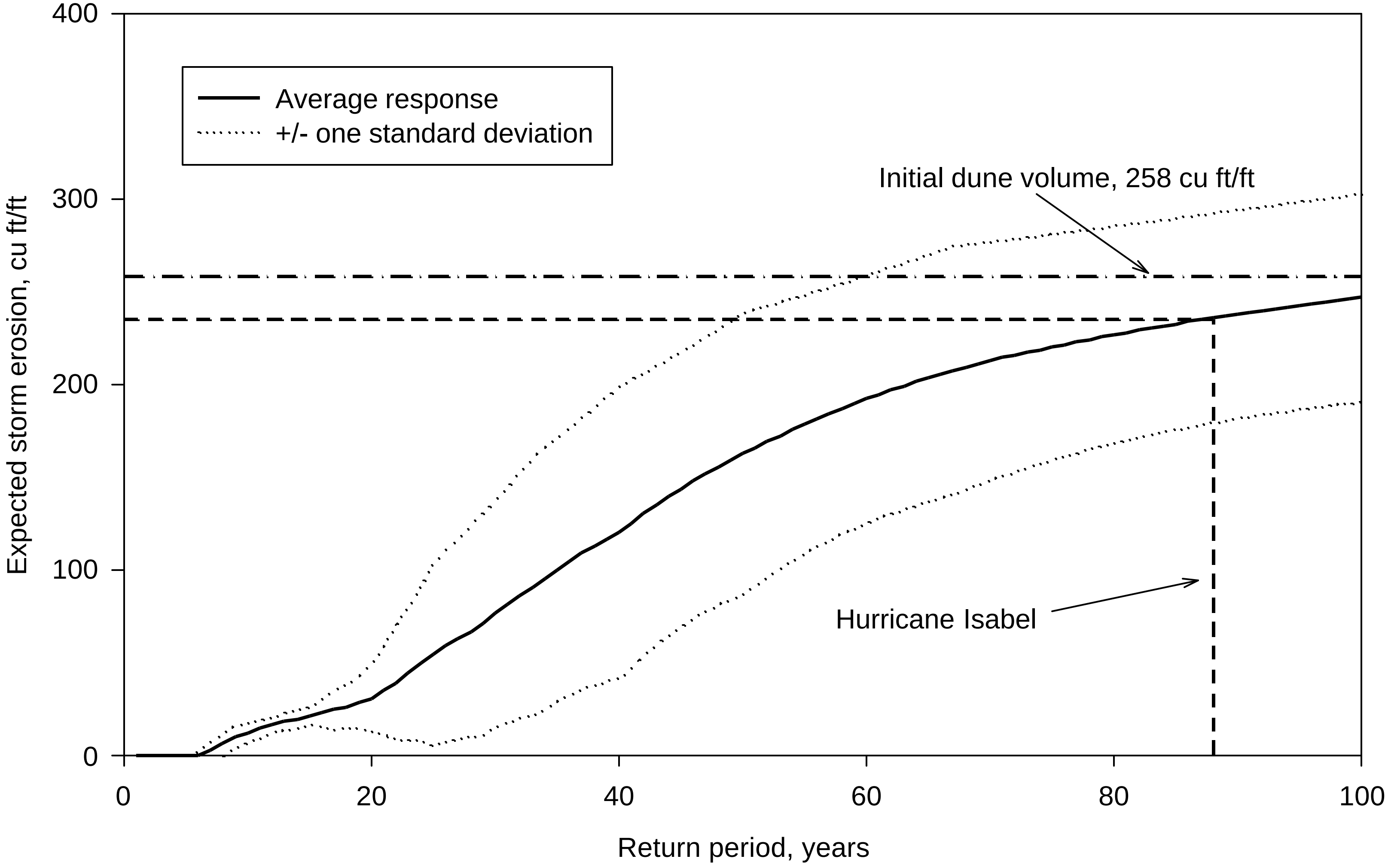

Figure 23f. Characterizing Hurricane Isabel with respect to expected storm erosion as a function of return period using EST results for transect NH7 at Kitty Hawk.

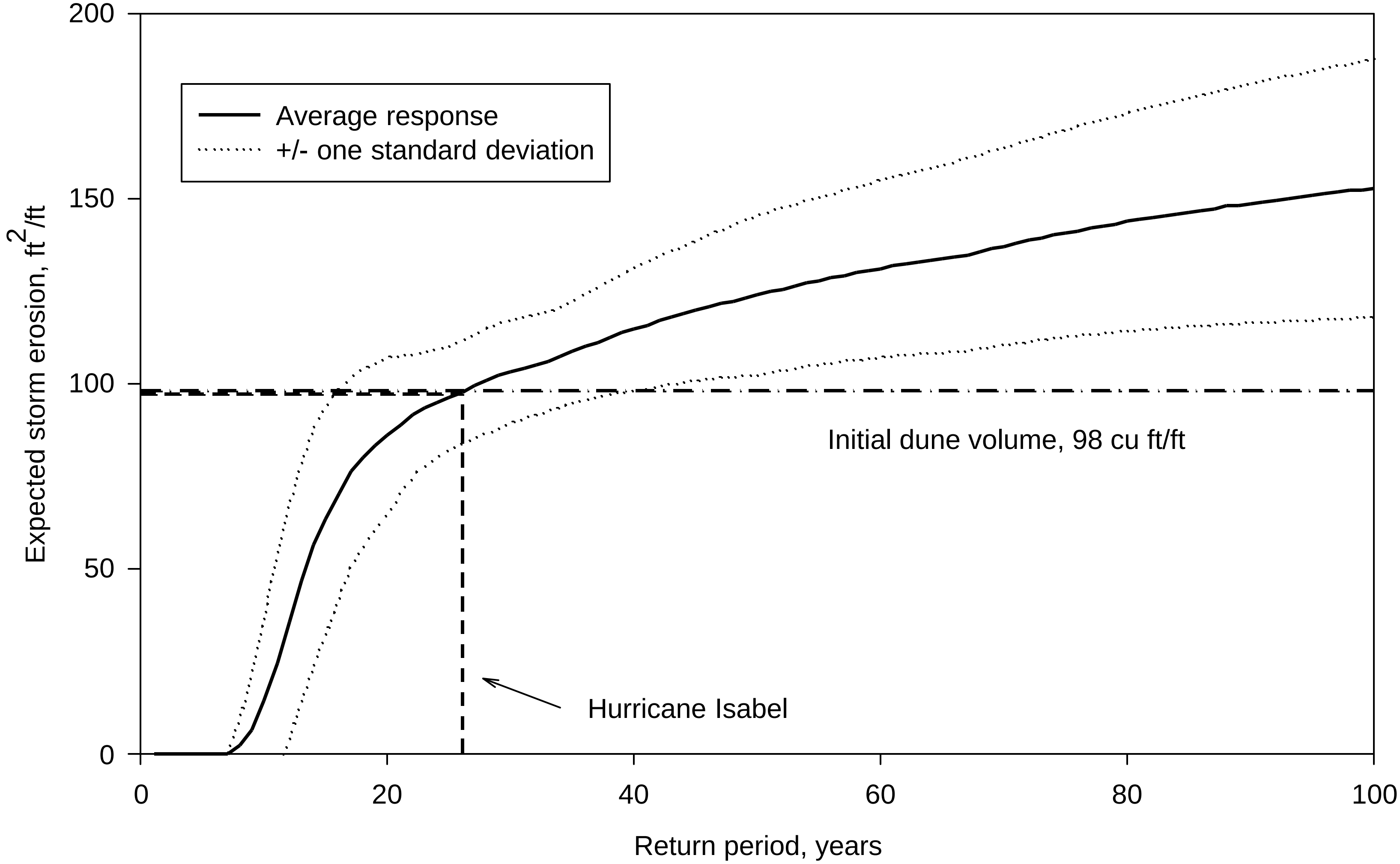

Figure 23g. Characterizing Hurricane Isabel with respect to expected storm erosion as a function of return period using EST results for transect NH8 at Kitty Hawk.

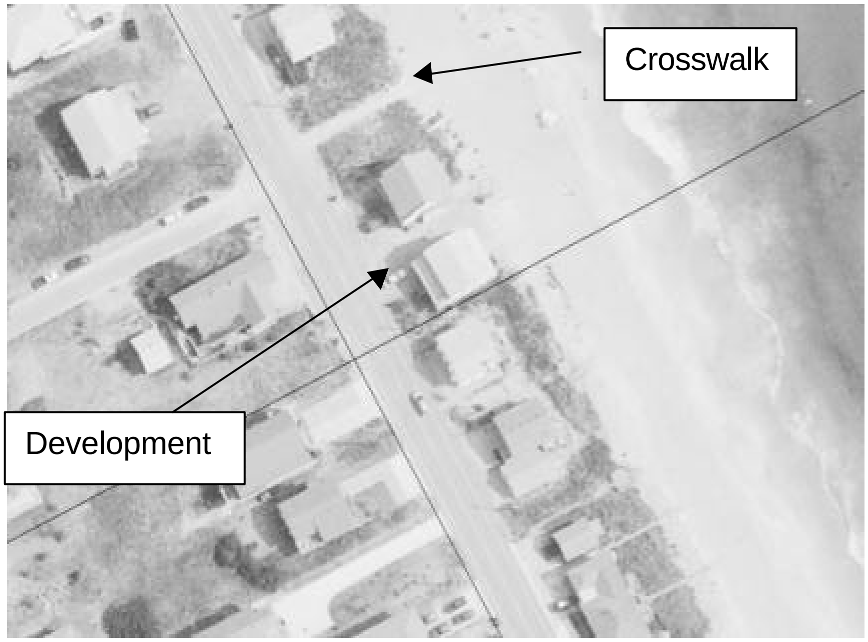

Figure 24. Transect NH5 with 1998 orthophoto showing robust vegetated dune and degradation of the dune due to cross walks and lot development.

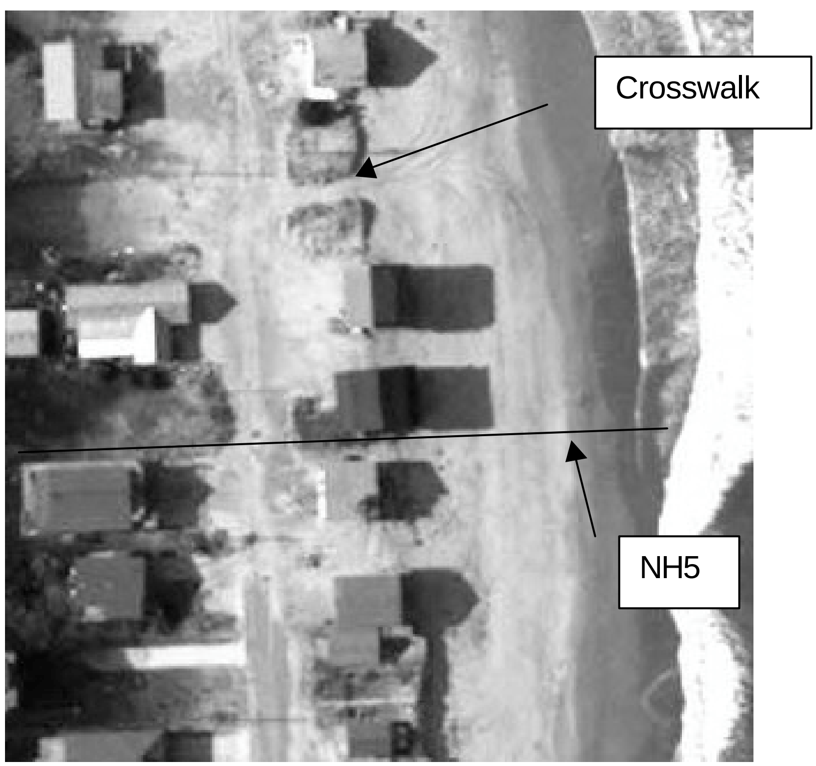

Figure 25. Transect NH5 with post Isabel NOAA imagery showing loss of dunes and overwash on HW 12.

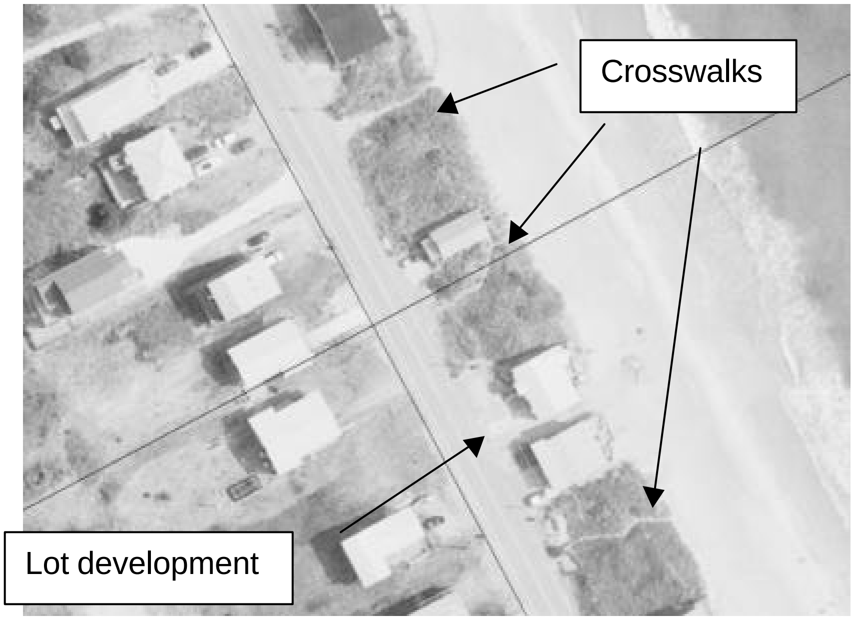

Figure 26. Transect NH6 with 1998 orthophoto showing robust vegetated dune and degradation of the dune due to cross walks and lot development.

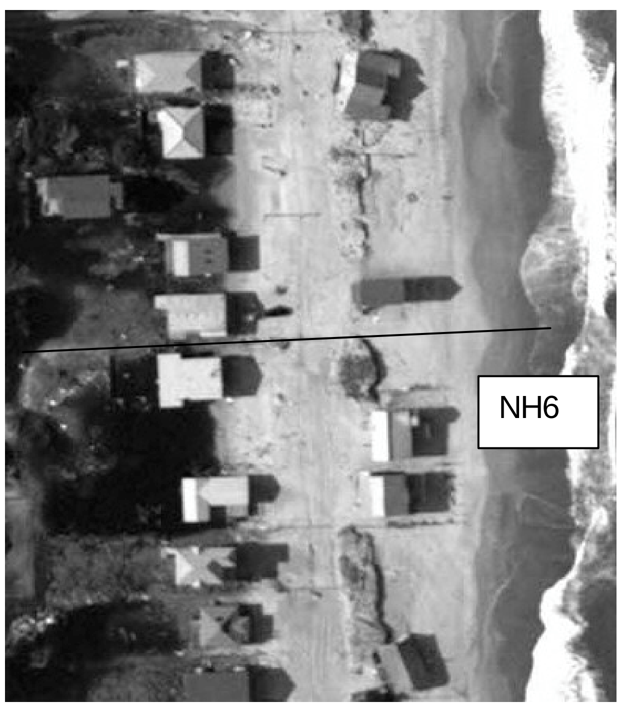

Figure 27. Transect NH6 with post Isabel NOAA imagery showing loss of dunes and overwash on HW 12.