Cape Hatteras National Seashore

Buxton, Dare County, North Carolina

Environmental Assessment

Beach Restoration to Protect NC Highway 12
Clean Water Act 404 and NPS Special Use Permits

At Buxton, Dare County, North Carolina

September 2015

Volume II: Appendixes A to G

APPENDIX A – LITTORAL PROCESSES

US ARMY CORPS OF ENGINEERS

US DEPARTMENT OF INTERIOR
NATIONAL PARK SERVICE

CAPE HATTERAS NATIONAL SEASHORE
NORTH CAROLINA

ENVIRONMENTAL ASSESSMENT

BEACH RESTORATION TO PROTECT NC HIGHWAY 12
CLEAN WATER ACT 404 AND NPS SPECIAL USE PERMITS
AT BUXTON, DARE COUNTY, NORTH CAROLINA

SEPTEMBER 2015

APPENDIX A

LITTORAL PROCESSES

Beach Restoration to Protect NC Highway 12 at Buxton, Dare County, North Carolina

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1.0 INTRODUCTION

This appendix supplements information in the main text of this document and provides additional data and analyses of erosion, wave climate, and littoral processes in the Buxton project area. It covers the following topics:

- Field data collection for beach condition surveys
- Beach and inshore profiles
- Analytical approach for defining beach condition
- Historical erosion rates (volumetric equivalents)
- Borrow area bathymetry
- Wave climate (NDBC / WIS)
- Wave transformation modeling before and after dredging
- Longshore sediment transport with and without the project
- Potential modification of longshore sediment transport due to offshore dredging

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2.0 BEACH CONDITION SURVEYS AND EROSION ANALYSIS

2.1 Data Collection Methods

CSE established a project baseline encompassing the length of Hatteras Island from Oregon Inlet to Cape Point using existing monuments. Stationing is in standard engineering units beginning near the Oregon Inlet jetty (station 0+00) and ending in the Cape Hatteras National Seashore (CHNS) (station 1983+77)*****. Intermediate control points mark the turning points and azimuths along the baseline.

*[*Stationing in engineering nomenclature is shorthand for distances along a line. In this case, station numbers increase from north to south so station 420+00 (for example) is 42,000 feet (ft) or ~8 miles south of the starting point near Oregon Inlet. Station 1792+50 (for example) is 179,250 ft or ~34 miles from the starting point.]*

Attachment 1-A lists the control points and applicable stationing along the baseline. The total length of the baseline is ~198,377 linear feet, and stations provide a convenient measure of distances along the shore. The Buxton community along the oceanfront begins near station 1880+00. The purpose of establishing one baseline for Hatteras Island (east coast) is to facilitate future island-wide erosion analyses.

The main area of interest for the present project is a 5-mile-long section extending north and south from Buxton between stations 1720+00 and 1980+00. Stations in this area were used to mark profile locations and compare variations in the beach condition. Table 2.1 lists some reference stations and localities along the baseline.

TABLE 2.1. Baseline (BL) and stationing along Hatteras Island for the present project at reference localities. See Attachment 1-A for list of control monuments (turning points) along the baseline.

Station	Monument #	Locality	Note
0+00	–	Oregon Inlet jetty	North end of BL
~347+00	–	Pea Island 2011 breach inlet	–
~635+00	–	Mirlo Beach	–
686+44	–	Rodanthe	BL turning point
~712+00	–	Rodanthe Pier	–
~1573+00	–	Village of Avon	–
~1880+00	–	Village of Buxton	North end of development
1928+11	CHL1	Old Hatteras Lighthouse site	–
1983+77	BYRD	Cape Point area	South end of BL

CSE's original data collection plan for a feasibility study called for profiles encompassing the littoral zone at spacing of 1,000–2,000 feet (ft). After CSE's initial deployment to the field (2013), the team received information about the USACE/NCDOT emergency nourishment plan for the S-curve at Rodanthe (USACE 2013). The Corps established a baseline specific to that project which used stations beginning ~1.6 miles north of Mirlo Beach. USACE station 0+00 corresponds to CSE station 548+94.

USACE officials (R Keistler, USACE–Wilmington, pers. comm., August 2013) provided information on their control points and profile lines for the emergency project. So as to develop consistent profile lines for future reference and comparison, CSE modified its 2013 data collection plan to match USACE profile locations to the extent practicable. This means that CSE's initial profiles fall on odd-numbered stations because of the offset between CSE's baseline and the USACE baseline. For example, USACE profile line 80+00 just north of Mirlo Beach is equivalent to CSE profile line 628+94.

At Buxton, initial profiles were run on odd-numbered stations in anticipation of potential future federal work in the area. Thus, "Phase 1" Buxton profiles are positioned slightly south (~63 ft) of even-numbered stations (ie – 1850+63, 1860+63, etc). During Phase 2 (2014) and planned future condition surveys, more profile stations were used for purposes of providing detail at 500-ft spacing. These lines were run from even-numbered stations along the Buxton project area to simplify nomenclature and references (ie – 1850+00, 1855+00, etc). Thus, the Phase 2 beach survey data does not perfectly overlay the Phase 1 data.

Figure 2.1 shows CSE's baseline, profile stationing, and profile azimuths for the Buxton area. A total of 20 stations around Buxton were profiled between the existing structures/ foredunes and deep water in August 2013, and 52 stations were surveyed in October 2014. Profile spacing was initially 1,000 ft along the center of the reach, and ~2,000 ft at the ends of the reach. Profile lines are shore-perpendicular to the baseline in most cases. Following a decision by Dare County to proceed with detailed planning for the Buxton project, profile spacing was set at 500 ft and the area of interest was expanded north to station 1720+00 (near Haulover Beach access in CAHA). [Azimuth information via starting and ending coordinates for each line is in Attachment 1-B.] CSE used a recent controlled vertical aerial image (source: ESRI Arc GIS World Imagery) as a reference for each line.

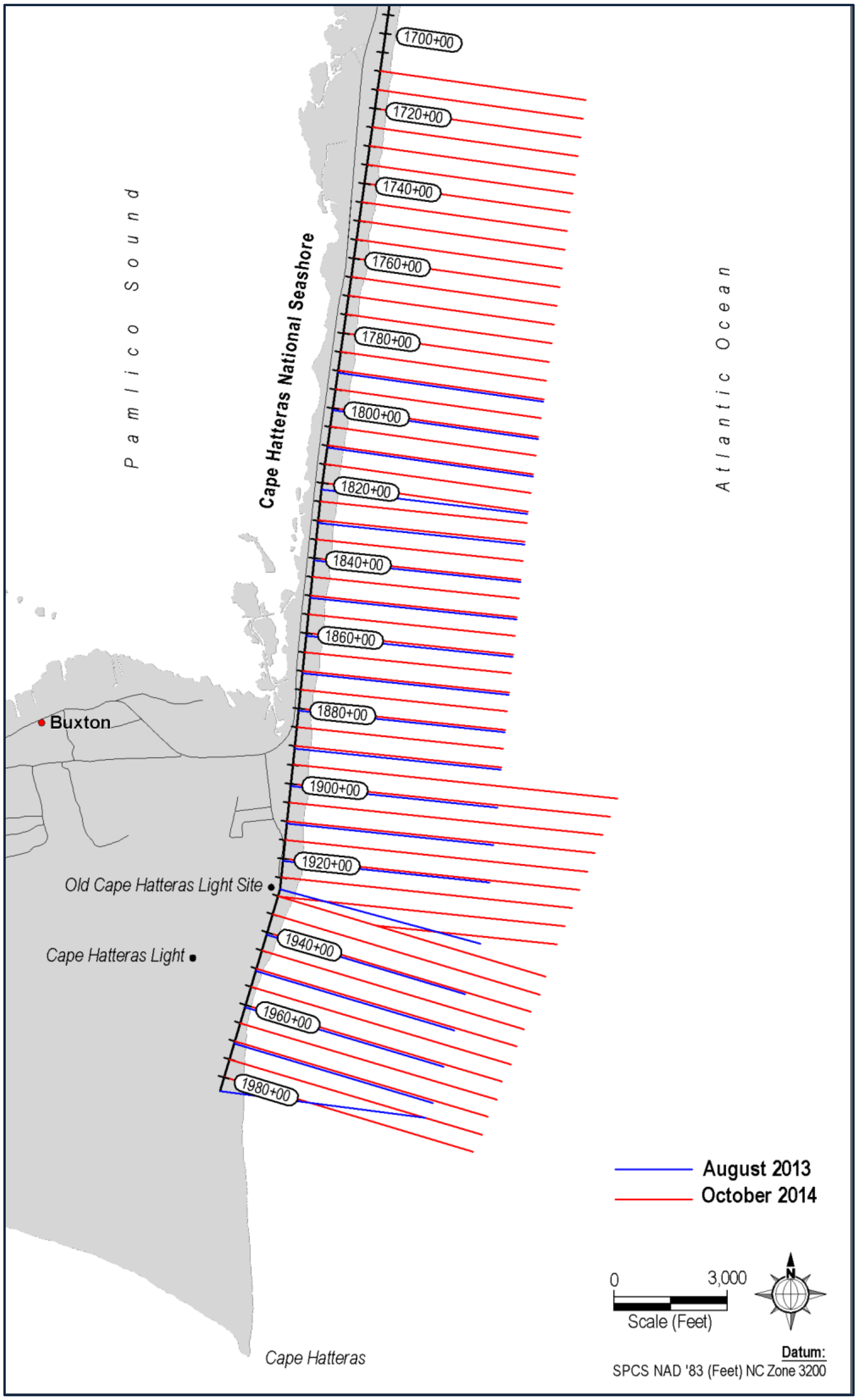


FIGURE 2.1. CSE's baseline, profile stationing, and profile azimuths for the Buxton area. Phase 1 profiles (August 2013) fell on odd-numbered stations for reasons given in the text. Phase 2 profiles at 500-ft spacing (October 2014) are positioned at even-numbered stationing for future convenience.

Vertical datum for CSE's profile data collection was NAVD'88 (North American Vertical Datum of 1988) which is ~0.4 ft above present mean tide level (MTL) in Dare County (NOAA-NOS). Figure 2.2 illustrates the various relationships among key reference datums for the closest tidal station at Cape Hatteras (NC) fishing pier, which is ~7 miles southwest of the Buxton project area. At the pier, mean ocean tide range is 3.0 ft with an average spring tide of 3.5 ft (NOAA Tides and Currents, station 8654400). Mean high water (MHW) is 1.05 ft above NAVD; mean tide level is 0.45 ft below NAVD; and mean low water (MLW) is 1.94 ft below NAVD. Horizontal datum used in CSE's data collection is NAD'83 (North American Datum of 1983, Zone: NC 3200).

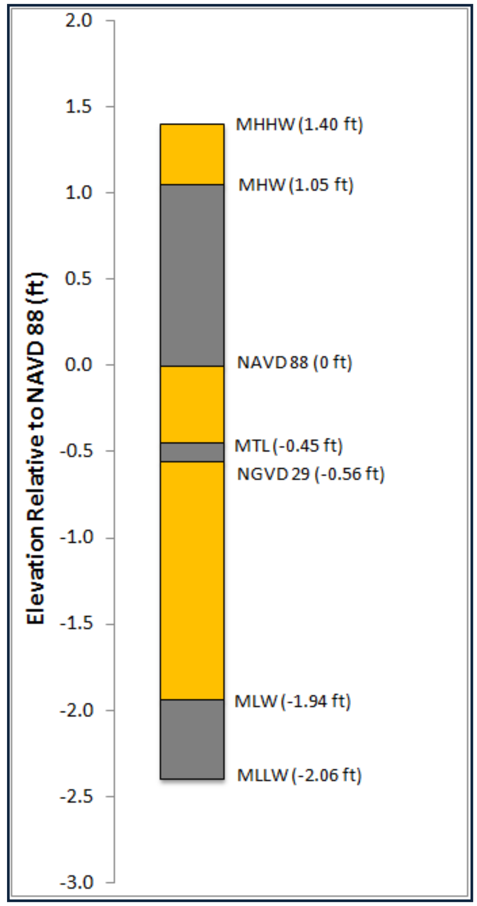


FIGURE 2.2. Key reference datums at Cape Hatteras (NC) fishing pier (~7 miles southwest of the project area).
[Source: NOAA-Tides and Currents Station ID 8654400]

Backshore, beach, and surf-zone topography and profile data were collected at low tide using a Trimble® R8 GNSS RTK-GPS. Land-based data collection included some backshore points extended inland to define the existing dune protection. These data were supplemented by LiDAR imagery obtained from:

http://www.csc.noaa.gov/digitalcoast/data/coastallidar/index.html.

Inshore profiles were collected at 5 H_Z using the Trimble® system linked to an ODOM Echotrac CVIOO™ precision fathometer mounted on CSE's 24-ft survey vessel, *RV Southern Echo*. Inshore surveys were obtained at higher tide stages to fill in the gap of the land-based data collected around lower tide stages. The survey profiles extended from low-tide depth into the nearshore area and the outer surf zone (~3,500–5,000 ft from the baseline). Figure 2.3 shows representative field data collection photos.

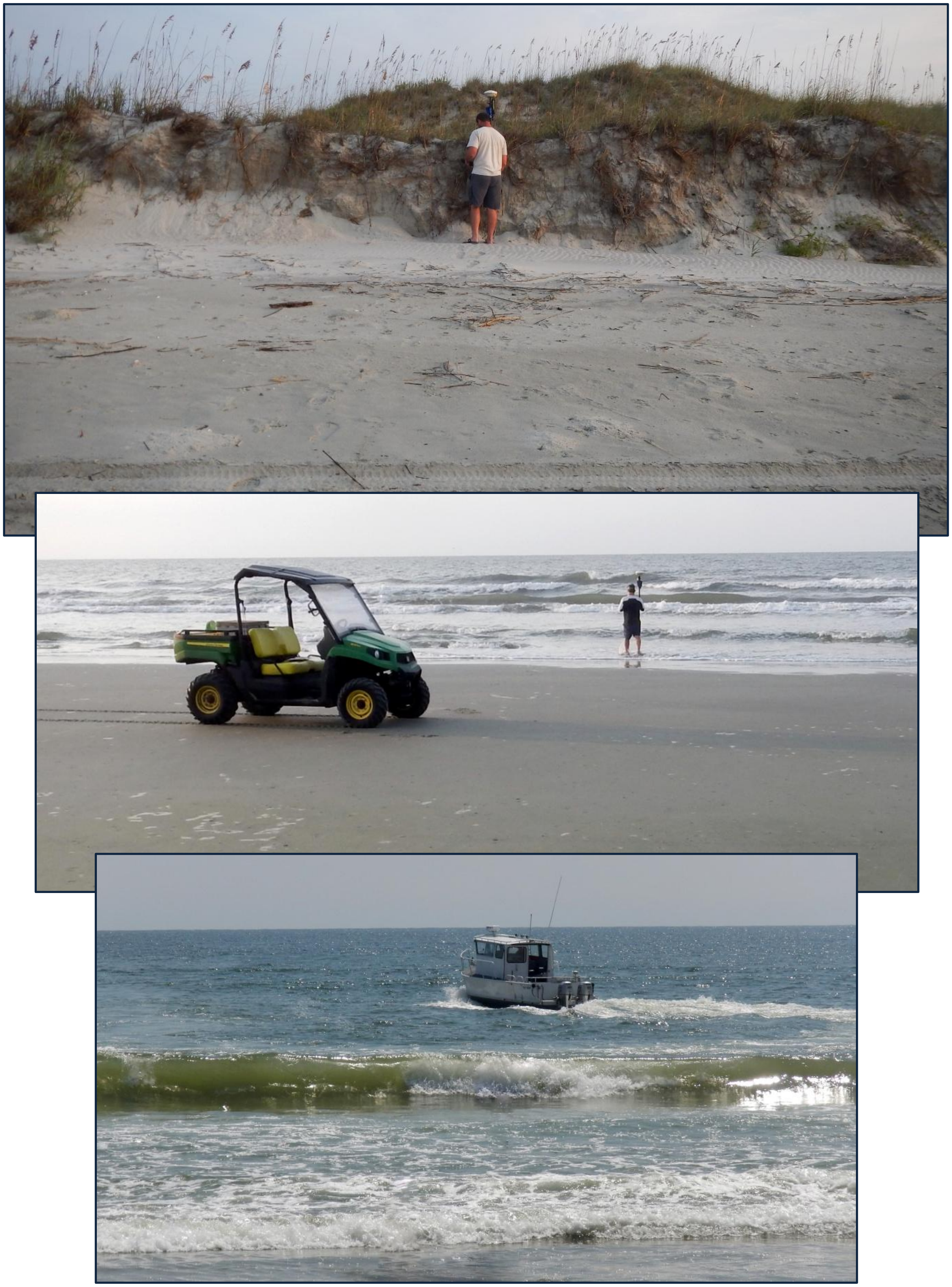


FIGURE 2.3. Field data collection methods involved subaerial survey using RTK-GPS at low tide and hydrographic surveys by boat at high tide. Fieldwork for Buxton was completed in August 2013 and October 2014.

The onshore and offshore data sets were merged and filtered to reduce the number of data points. Additionally, offshore points were smoothed using a 7-point floating-point average, and the data were checked for anomalies. Data collected in x-y-z format were used directly for purposes of developing a digital terrain model (DTM), which provides a three-dimensional picture of the beach, the longshore bar, and the offshore zone.

Figure 2.4 illustrates DTMs of the Buxton project area by color-coded, smooth-contour maps using the indicated elevation/depth intervals for each color. Red and orange are the dune-beach zone; yellow marks the longshore bar; and blue represents water depths >30 ft. The bathymetry DTMs show relatively smooth, continuous morphology of a longshore bar (yellow-green color band) inside the 20-ft depth contour along Buxton positioned about 1,200 ft offshore with a crest elevation of (~)−12 ft to −14 ft.

2.2 Beach Profiles

Although sediment transport and morphology changes in the nearshore are three-dimensional, it is customary in beach analysis to separately consider the cross-shore and planform (ie – alongshore) evolution. Survey data (collected in x-y-z format) were converted to x-z (distance-elevation) pairs for purposes of comparing beach conditions among profile lines. Because no recoverable historical profiles into deep water were found by the team, it was not possible to make direct comparisons of historical profiles with the present condition surveys.

Representative profiles from the August 2013 and October 2014 surveys are shown in Figure 2.5. [See Figure 2.4 for general locations.] Attachment 2 contains the set of profiles obtained by CSE in August 2013 and October 2014. All Buxton area profiles in October 2014 exhibited a longshore bar with a crest at ~13–15 ft NAVD. The bar crest is broader, deeper, and further offshore at the southern end of Buxton along the National Seashore (south of the groin field at the old Cape Hatteras Lighthouse location).

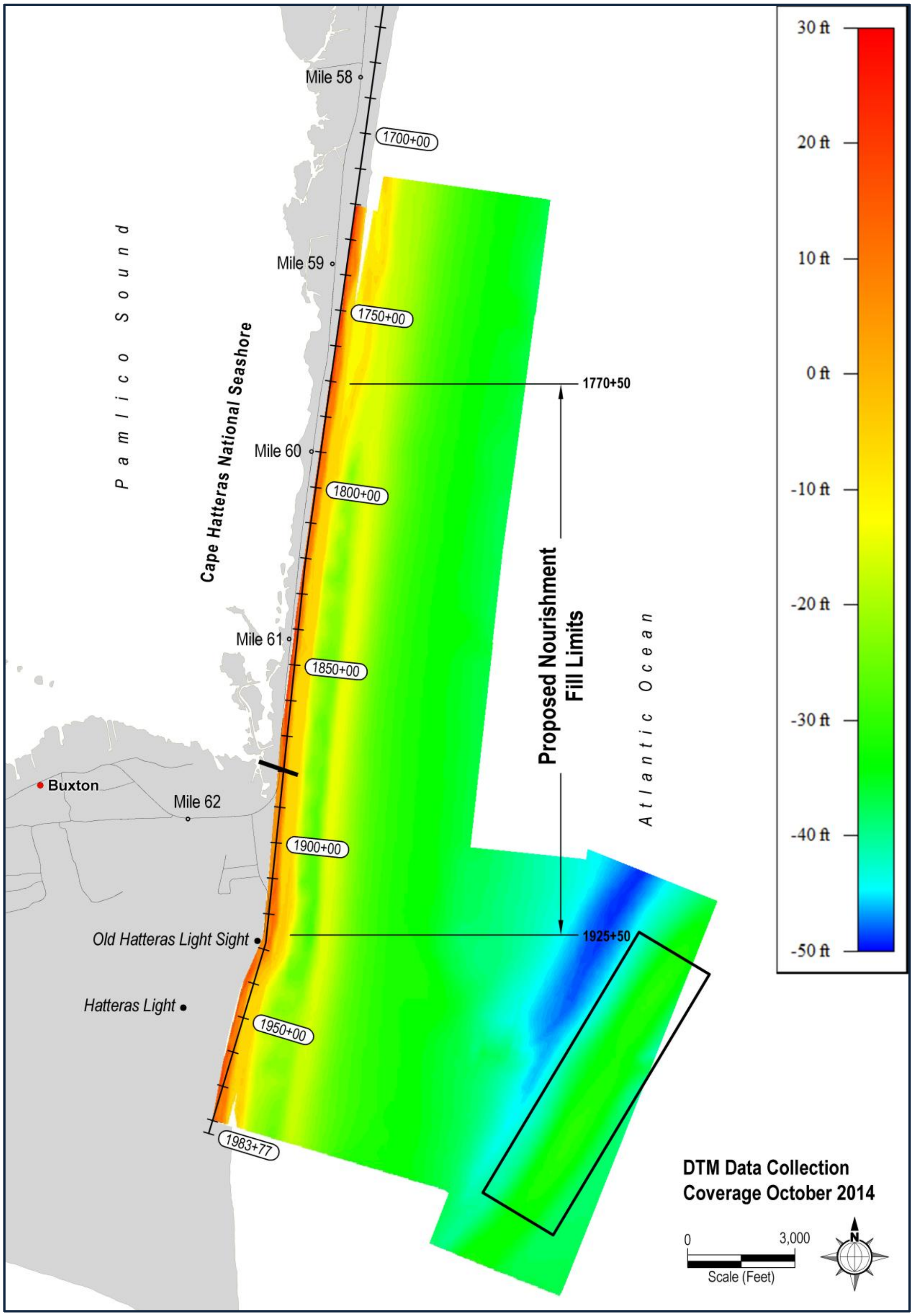
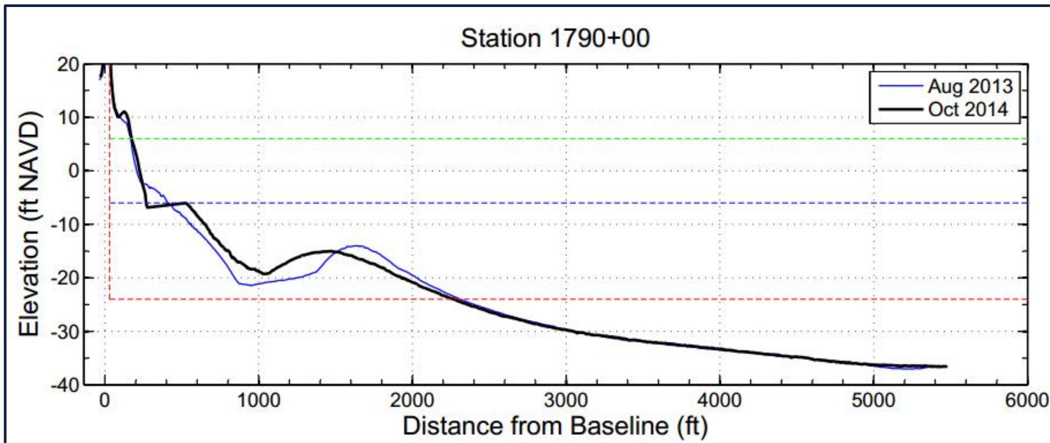
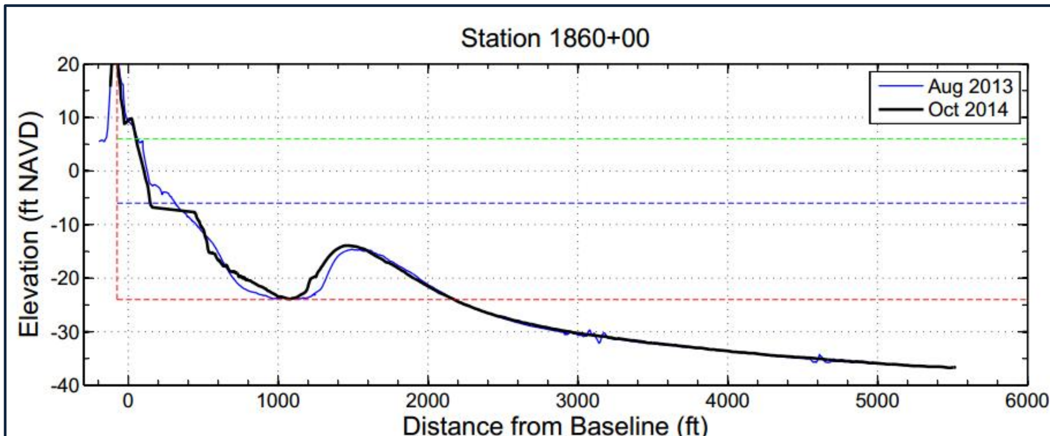


FIGURE 2.4. Color-coded topography and bathymetry DTM interpolated from the October 2014 survey for the Buxton project area. Note variations in water depth (and profile geometry) between the outer bar and the beach. The "salient" in the shoreline between stations 1890+00 and 1980+00 is sand retained by groins at the old Cape Hatteras Lighthouse site. The alignment of the offshore bar is straighter than the shoreline north and south of the salient.



Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	27.0	120.7	838.3
Oct 2014	28.8	115.6	894.4



Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	29.7	131.3	771.8
Oct 2014	24.3	103.4	774.4

FIGURE 2.5. Representative profiles for the Buxton project area at stations 1790 and 1890 in CHNS.

2.3 Profile Volume Approach

Beach/inshore profiles were analyzed using CSE's Beach Profile Analysis System (BPAS) software which facilitates statistical analysis, volume change calculations, and graphing. Profile volumes are a convenient way to determine the condition of the beach and compare one area with another. As Figure 2.6 illustrates, the active littoral zone encompasses a broad area between the dunes and some limiting offshore depth. Each profile incorporates complex topography which changes continually as the beach adjusts to varying wave energy, sediment supply, and tide range. Storms modify the profile by shifting sand from the dry beach and foredune to the outer surf zone. After storms, fair-weather waves tend to move sand back to the visible beach and reshape protective longshore bars. If this cycle of offshore/onshore sediment transport remains balanced over time, the beach will be stable with no net loss of volumes in the profile. However, if more sand moves offshore or down-coast over time than returns to the visible beach, there will be a net loss and a certain volume erosion rate.

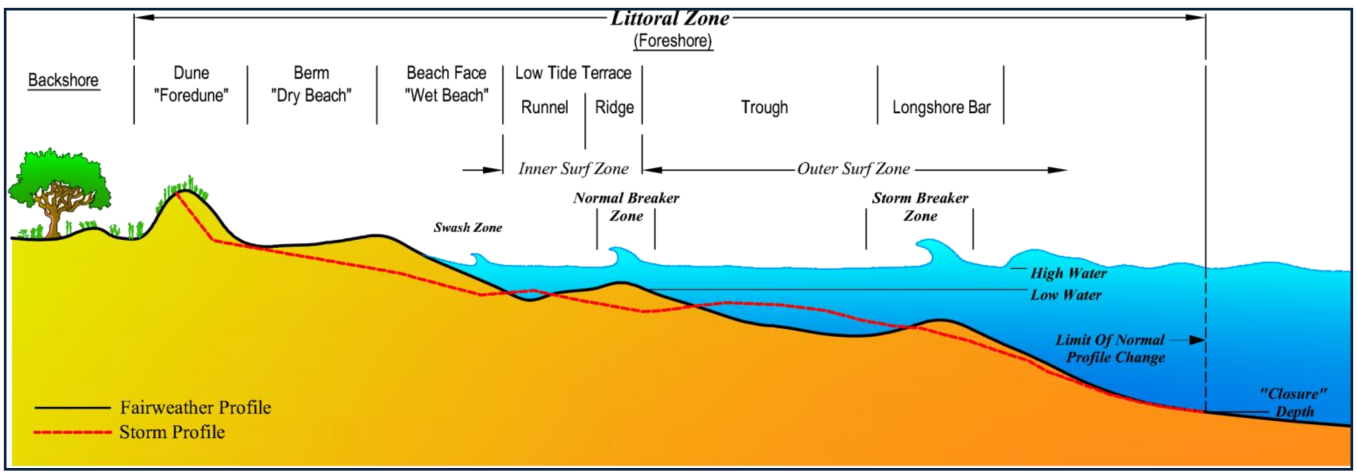


FIGURE 2.6. Representative profile of the littoral zone illustrating the principal features between the dune and offshore. The profile varies with changes in wave energy, the passage of storms, and differences in sediment quality. The Buxton erosion analysis takes into account the cycle of beach profile changes and focuses on the sand volumes in the entire littoral zone. [Based on Komar 1998]

While it is possible to approximate the equilibrium shape of beach profiles by simple analytical equations (Dean 1991, 2002), each site has a unique set of coastal processes (waves, tides, and nearshore currents) as well as complex admixtures of sediment. The morphology and slopes across the surf zone vary significantly as sediments of differing sizes are sorted by waves. Coarsest material tends to concentrate in shallow water at the inshore breaker line. Finer sands tend to accumulate on the longshore bar (if present) and foredune.

As Komar (1998) and many others have shown, coarser sediments tend to produce steeper foreshore slopes (see Fig 2.6) than fine sand, assuming wave energy is similar. The implication is that less coarse sand is required to establish a profile in equilibrium with the local waves and tides compared with a beach consisting of very fine sand. This is illustrated in Figure 2.7. The example in the graphic compares a typical cross-section through a Louisiana barrier island with the North Carolina coast. Much of the Louisiana coast consists of very fine sand and experiences relatively low wave energy. Barrier islands are low-relief with very broad platforms extending miles offshore. North Carolina Outer Banks barriers are composed of much coarser sands which tend to equilibrate at steeper slopes despite higher wind and wave energy. As a result, a cross-section through a North Carolina barrier island will have higher relief compared with Louisiana.

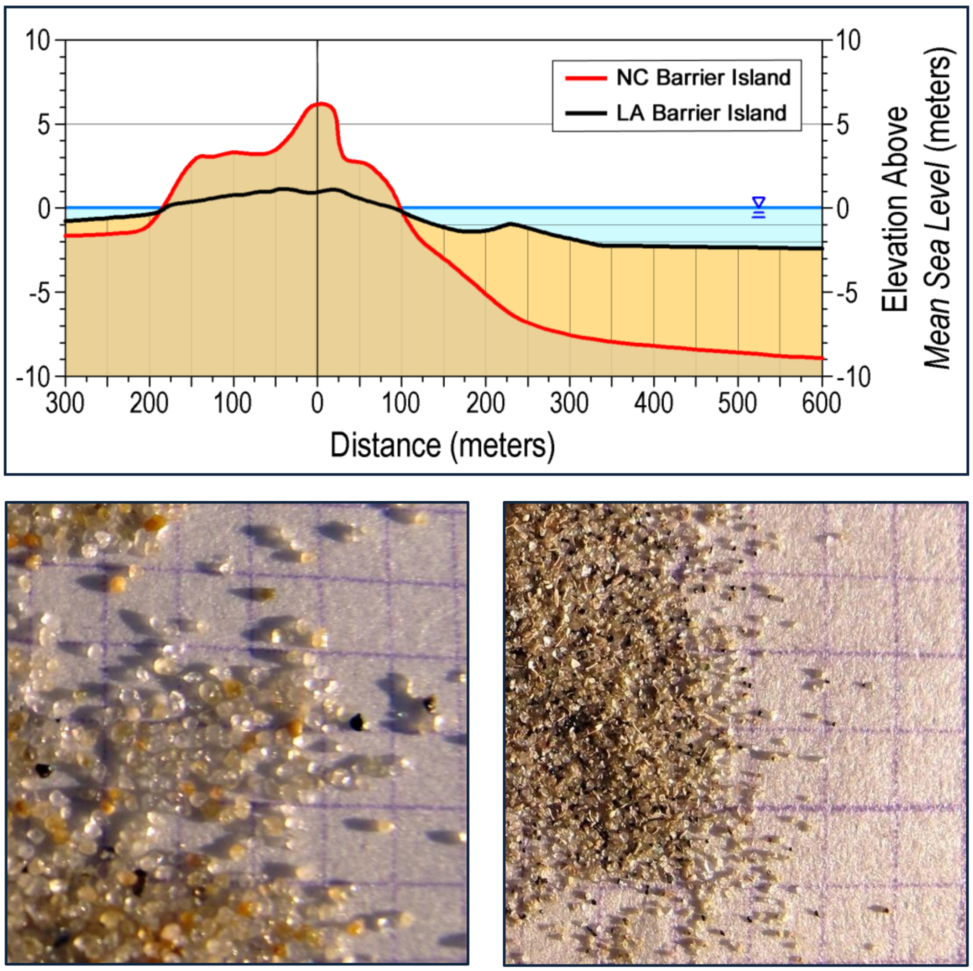


FIGURE 2.7. Variation in equilibrium barrier island and foreshore profiles for Louisiana and North Carolina. Coarser sandy sediments [typically 0.4 millimeters (mm) grain size] (left) lead to steeper profiles and less volume in the base of North Carolina barrier islands relative to Louisiana which is founded on fine-grained sediments (typically ~0.1 mm grain size) (right). Ocean is to the right on the diagram. Note: 1 meter ≈ 3.28 ft. [From CSE 2011a]

Researchers have found that basic differences among beach profiles can be distinguished by simple measures of profile volumes (eg – Verhagen 1992, Kana 1993). Profile volumes convert a two-dimensional measure of the beach to a "unit volume" measure as illustrated in Figure 2.8. Using common datums and similar starting points (say, near the dune crest), it is possible to calculate the volume of sand contained in a unit-length of beach.

Profile volumes integrate all the small-scale perturbations across the beach and provide a simple objective measure of beach condition (Kana 1993, Kana et al 2015). They provide quantitative estimates of sand deficits or surpluses when compared against a target or desirable beach condition.

The examples of profile volumes in Figure 2.8 show a "normal" beach with a representative unit volume of 100 cy/ft measured to low-tide wading depth.

A normal healthy profile is generally considered to consist of a stable foredune and a dry beach that is wide enough to undergo normal seasonal and storm changes without adverse impact to the dune or backshore development.

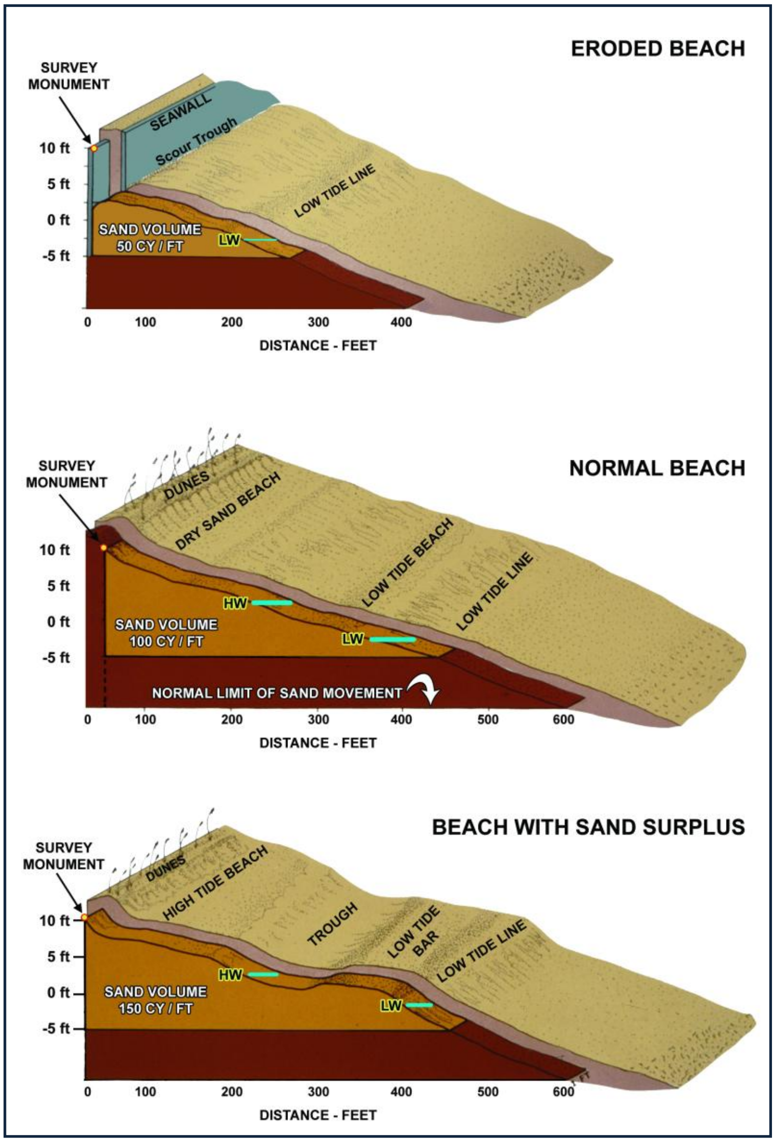


FIGURE 2.8. The concept of unit-width profile volumes for a series of beach profiles showing an eroded beach with a deficit, a normal beach, and a beach with a volume surplus. Profile volumes integrate small-scale perturbations in profile shape and provide a simple objective measure of beach condition. Indicated quantities are realistic for many East Coast beaches within the elevation limits shown. [After Kana 1990]

The other profiles in the graphic illustrate values for an eroding beach (in this case, backed by a seawall) and a beach with a sand surplus. For this simple example, the unit volume of the eroded profile is 50 cy/ft, or ~50 percent of the normal beach. The third profile illustrates a beach with a surplus of sand along the dry beach and wet-sand beach relative to a normal healthy profile. Such areas often reflect accreting conditions where shallow bars are welding to the beach near inlets. The calculation limits can be arbitrary as long as they are consistently applied. Ideally, they should encompass the entire active zone of profile change for the time period(s) of interest.

It should be readily apparent that at least 50 cy/ft must be added to the eroded profile in Figure 2.8 to achieve a normal, healthy profile. [In actuality, much more sand is required to account for the area between low-tide wading depth and the offshore limit of significant sand movement (see Fig 2.6).] Analyses such as these are necessarily site-specific, but they are practical measures of sand deficits and erosional losses over time.

2.3.1 Reference Contours and Boundaries for the Project Area

Volume variations along the Buxton project area were estimated using standard methods (average-end-area method) and common cross-shore boundaries and contour datums. Two primary lenses (ie – volumes between particular reference contours) were used in the analysis for purposes of evaluating the condition of various portions of the profile. Emphasis was on the overall volume of sand contained from the foredune to a depth beyond the outer-most bar. A related volume seaward of structures was also determined.

CSE assumed that the normal limit of significant change in bottom elevation (ie – "depth of closure" – DOC) for the project area is −24 ft NAVD. This depth is based on estimates of DOC at decadal scales at Duck (Birkemeier 1985), Bogue Banks (Olsen 2006), and Nags Head (Kaczkowski & Kana 2012). Therefore, unit volumes are referenced to −24 ft NAVD and encompass the volume in the longshore bar. Figure 2.9 illustrates the cross-sectional areas of these two lenses.

The first reference volume uses the foredune crest as a starting point as illustrated in Figure 2.9. The dune crest is a convenient point of comparison because it tends to mark the sea-ward edge of stable vegetation and defines the morphology and shoreline azimuth along beaches away from inlets. The dune crest position varies less than the daily high watermark (surf swash line) or any contour along the intertidal beach zone.

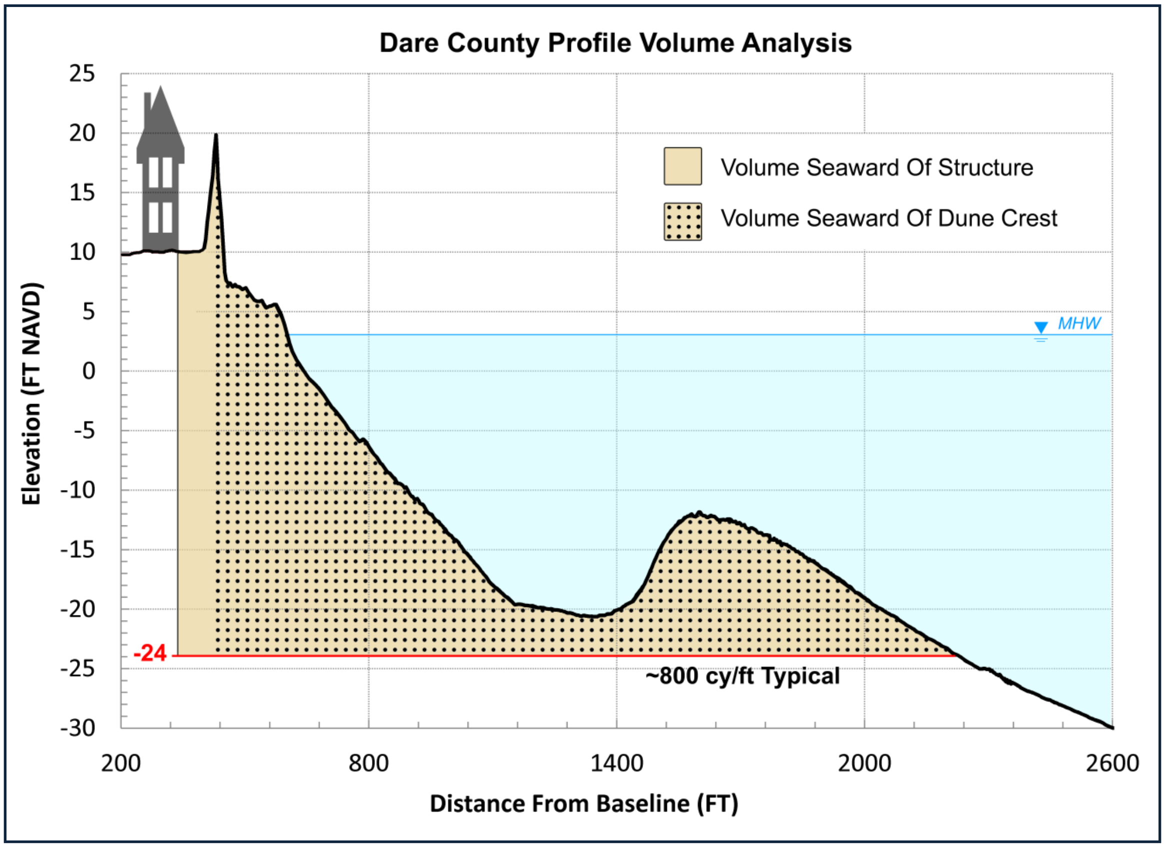


FIGURE 2.9. Illustration of the two lenses used in the profile volume analysis for Buxton. The first volume quantifies sand contained between the approximate foredune crest and −24-ft NAVD. The second calculates the volume between the seawardmost structure in the vicinity of the profile and −24-ft NAVD. Based on typical dimensions in the project area, the hatched cross-section shown here has a 2-D area of ~21,600 square feet. This is equivalent to a "unit volume" of 800 cy/ft (ie – 800 cy are contained in a 1-ft section of beach – see Fig 2.8).

Variations in dune position (seaward vegetation line) can obviously occur in areas where the dunes have been manipulated by scraping or breached during storms. To account for such variations, CSE checked the indicated dune position (on surveyed profiles) against the overall shoreline morphology and adjusted the reference calculation starting point as necessary to minimize volume variations associated with major offsets in dune position (or starting distances for calculations) among adjacent stations.

The second reference volume uses the seawardmost structure in the immediate area (edge of Highway NC 12 or seaward face of building) as the landward reference point (Fig 2.9). This calculation provides a measure of how much extra sand is contained in the profile seaward of structures relative to the quantity in the active beach zone. Where buildings are situated on the active beach, profile volumes will be lower than the volume from the dune crest.

While the selection of volume calculation limits is arbitrary, the utility of this approach is that the relative condition of the beach from locality to locality can be objectively compared. Areas which contain a stable dune and wide beach seaward of structures can serve as a reference healthy condition for areas of high erosion and large sand deficits.

2.3.2 Profile Volume Variations in the Project Areas

Profile volumes in the project area are listed by station in Table 2.2. The results include one set of volumes from the dune crest and a set of volumes from the seawardmost structure line. The calculations extend to −24 ft NAVD. The table also includes reference calculation starting distances with respect to the project baseline for future reference. Stations have been grouped into "upcoast," "downcoast," and "critically eroding" sections based on visual observation of conditions in the field and the calculated volume. Figure 2.10 illustrates the systematic variation in profile volumes along the shore.

The distinctive trend for the project area is the significant drop in volume near the center of the reach. The profiles in Buxton have a mean profile volume of ~800 cy/ft seaward of the dune crest. However, a central group of profiles, representing ~7,000 ft of shoreline centered on the Village of Buxton, average <630 cy/ft. Figure 2.10 shows even greater variation in profile volumes seaward of structures with a mean of ~900 cy/ft in the Buxton project reach. However, some stations in the middle of the reach contain <600 cy/ft.

The graphs in Figure 2.10 show a smoothed, best-fit trend line (complex polynomial) illustrating the systematic variation in profile volumes. The coefficient of determination (r^2) is relatively high in each case, confirming the consistency of the trend. At quick glance, the data indicate which sections of shoreline can be considered critically eroding. For Buxton, the reach between stations 1870+63 and 1940+63 has ~78 percent of the average unit volume seaward of the dune crest (Table 2.2). These data provide a direct estimate of sand deficits in critically eroding areas relative to adjacent healthy beach areas.

Upcoast stations north of Buxton have a minimum of ~830 cy/ft, and downcoast stations exceed over 900 cy/ft. The result for Buxton downcoast stations is biased by the large offset in the shoreline south of the groin field near Cape Hatteras Lighthouse. The data (Attachment 2) confirm that downcoast profiles in the Cape Point area have a wider zone between the dry beach and the longshore bar. As previously illustrated in Figure 2.4, the longshore bar maintains a straighter alignment offshore than the shoreline. The landward shift of the dune crest and wider downcoast profiles account for their higher volumes.

TABLE 2.2. Unit volumes by station in the Buxton area (August 2013) between the approximate foredune crest and −24 ft NAVD, and the seawardmost structure in the locality and −24 ft NAVD based on the condition survey of August 2013. [*Includes shoreline distance to prior upcoast and downcoast stations]

CSE	USACE	Distance To	Calc Starting Pt From Baseline (ft)		Unit Volume (cy/ft) to -24 ft	
Station	Station	Next (ft)	At ~Dune Crest	At ~Seaward Structure	From Dune Crest	From Structure
1790+63	N/A	1000	-206	30	838.3	1206.2
1800+63		1000	-200	0	862.1	1109.3
1810+63		1121	-189	-60	910.8	1093
1821+84		879	-150	-60	885.8	1035
1830+63		1000	-157	-85	909.4	1006.3
1840+63		1000	-161	-60	770.2	924.4
1850+63		1000	-166	-65	744.9	896.1
1860+63		1000	-160	-75	771.8	896.2
1870+63		1000	-135	-70	768.9	856.8
1880+63		1000	-86	10	673	801
1890+63		1000	115	50	656.4	576.7
1900+63		1000	106	115	598.3	610.9
1910+63		1000	40	110	650.6	744.1
1920+63		748	-55	170	593.2	870.5
1928+11		1252	145	100	603.4	549.8
1940+63		1000	-185	-185	878.3	878.3
1950+63		1000	-210	-210	975.6	975.6
1960+63		1000	-135	-135	992.3	992.3
1970+63		1314	-55	-55	1015.7	1015.7
1983+77			130	130	966.6	966.6
Totals/Averages						
All Stations		**19314**	**N/A**	**Average:**	**803.3**	**900.2**
(1790+63 to 1983+77)				Std Dev:	139.9	175.5
Upcoast Stations		**8000**		**Average:**	**829.1**	**1002.6**
(1790+63 to 1870+63)				Std Dev:	66.1	118.4
Downcoast Stations		**4314**		**Average:**	**965.7**	**965.7**
(1940+64 to 1983+77)				Std Dev:	52.3	52.3
Critically Eroded Stations*		**7000**		**Average:**	**629.2**	**692.2**
(1880+63 to 1928+11)				Std Dev:	34.7	131.6

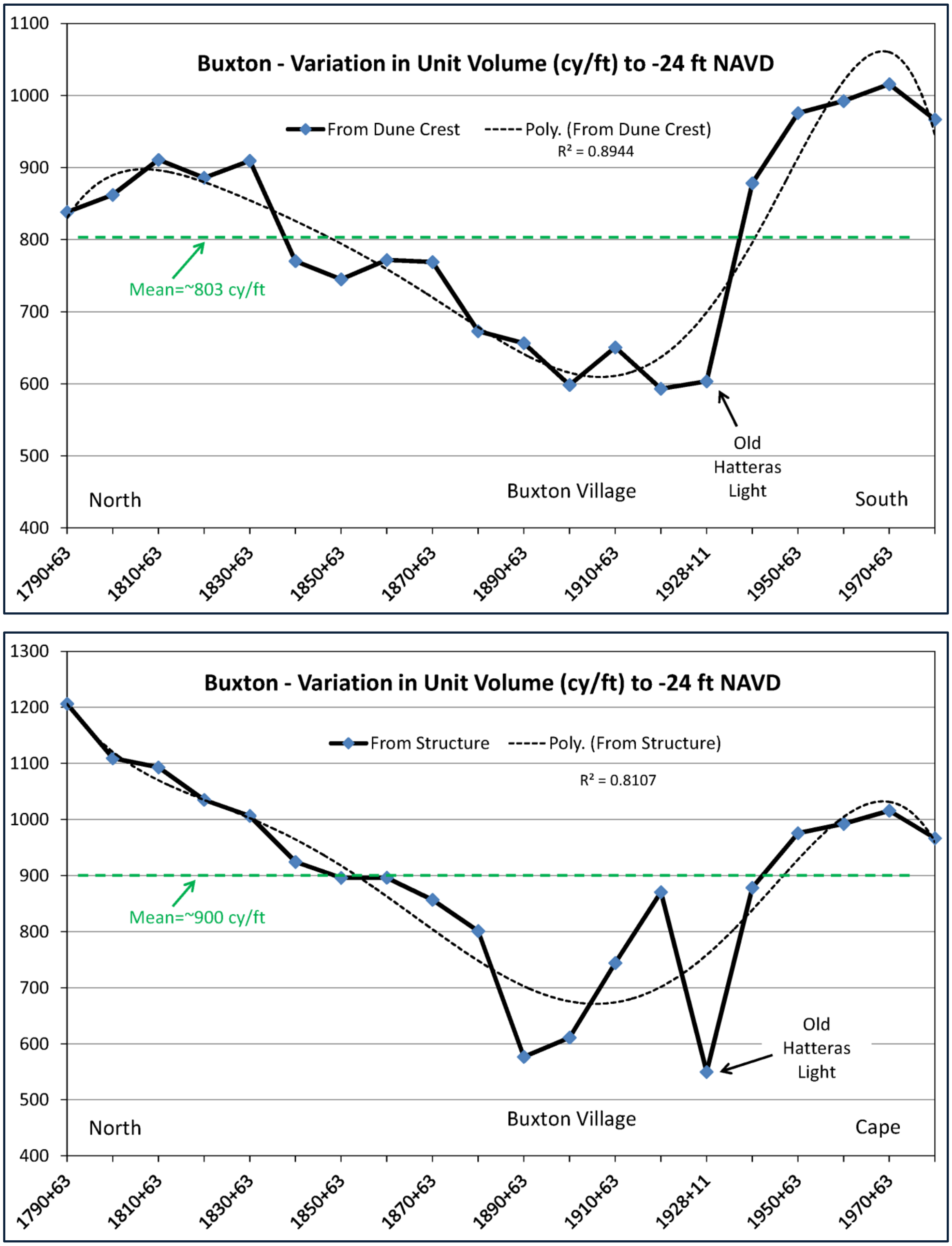


FIGURE 2.10. Profile volumes by station in the Buxton area in August 2013 computed to −24 ft NAVD (upper) relative to the foredune crest and (lower) relative to the seawardmost structure in the vicinity. A shore-protection structure in the vicinity of the old Hatteras Lighthouse site accounts for the "outlier" in the lower graph.

2.3.3 Volumes in Dunes

CSE also calculated unit volumes for other contour intervals as shown in the tables associated with each profile in Attachment 3. These "lens" limits help define the quantity of sand contained in various cross-shore zones such as the foredune above +10 ft NAVD (ie – toe of dune) seaward of the dune crest or structures, or the visible active beach between the toe of dune and mean low water (approximately −2 ft NAVD). The tables in Attachment 3 show a typical volume seaward of the foredune crest in the zone between +10 ft and −2 ft NAVD (visible active beach) is in the range 50–80 cubic yards per foot (cy/ft). The overall profile volume between the dune crest and −24 ft NAVD is in the range ~600–1,000 cy/ft. Profile volumes increase with depth, of course, but they also become more variable proceeding offshore because of variations in the longshore bar. [Minor imprecisions inherent with all profile surveys also accumulate with distance.]

For the project area, elevation +8.5 ft NAVD is a convenient reference for storm protection relative to federal guidelines for dune protection along developed beaches. FEMA has developed a criterion to evaluate whether a dune is likely to be an effective barrier to storm surges and associated wave action during the base flood event (100-year storm). This criterion is also applied in estimating the landward extent of the base flood event and has come to be known as the "540 Rule" (FEMA 1988, 2005). The FEMA 540 Rule definition states:

> *". . . primary frontal dunes will not be considered as effective barriers to base flood storm surges and associated wave action where the cross-sectional area of the primary frontal dune, as measured perpendicular to the shoreline and above the **100**-year still-water flood elevation and seaward of the dune crest, is equal to, or less than, **540** square feet (**20** cubic yards)."*

The 100-year, still-water flood level (SWFL) in the project area is (~)+8.5 ft NAVD***** (FEMA 2006) Therefore, applying the above definition, Buxton dunes should contain a minimum of 20 cy/ft above the +8.5-ft NAVD contour to approach FEMA-recommended protection levels.

> *[*Based on FEMA 2006 Transect #131 ~3,500 ft north of Rodanthe pier. The SWFL for other transects in the project area varies slightly from 8.5 ft NAVD.]*

CSE evaluated the condition of the dune system by measuring seaward from the dune crest to +8.5 ft NAVD at each profile line. A similar calculation was made from the seawardmost major structure line along the oceanfront. Figure 2.11 illustrates application of this dune volume criterion where houses are present on the foredune using the profile volume analysis.

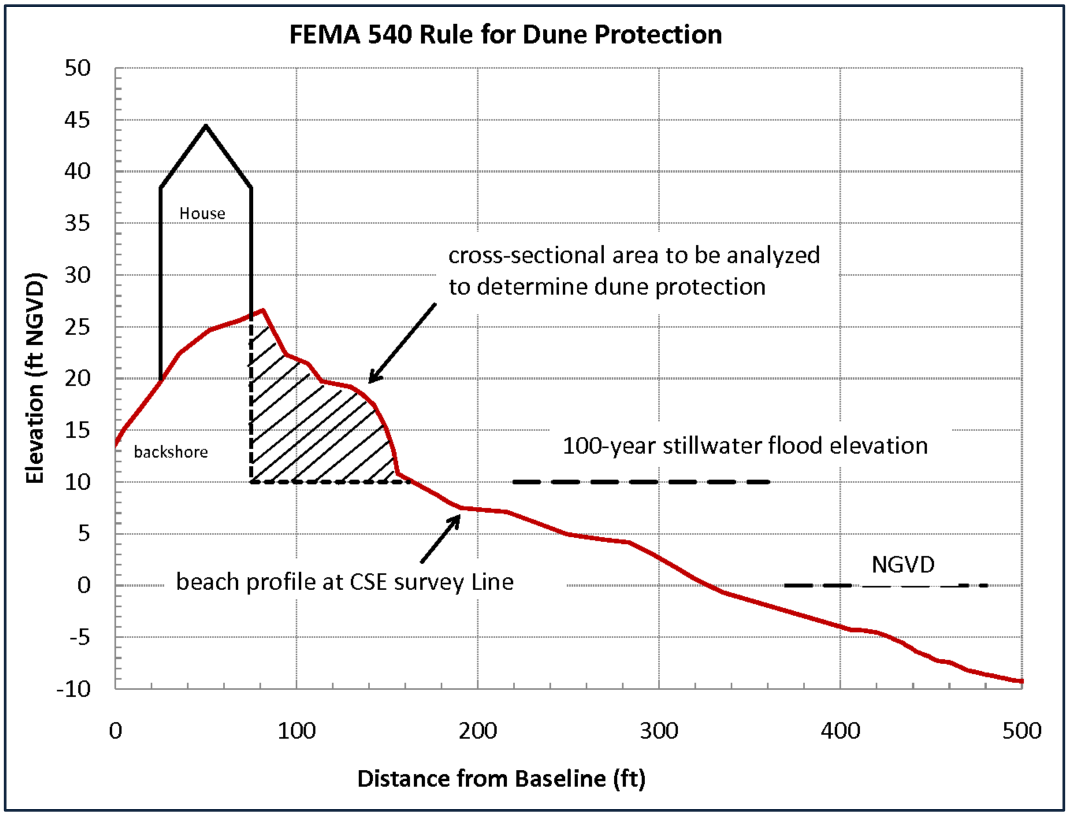


FIGURE 2.11. Example of dune and beach cross-section (profile) showing application of the FEMA "540" rule for protection. A cross-sectional area of 540 square feet (equivalent to 20 cy/ft) situated above the 100-year stillwater flood level (base flood elevation) is considered to be the minimal dune volume needed to sustain a major storm and protect properties. The generic example in the diagram uses a different datum and flood elevation. For Buxton calculations, +8.5 ft NAVD is assumed for the 100-year stillwater flood elevation, although there is some small variation in this level along Hatteras Island. [Source: FEMA 2005, 2006]

Table 2.3 lists the "dune" volumes above the 100-year approximate base flood elevation of 8.5 ft NAVD in the project area. The first set of volumes extends from the foredune crest and the second set from the seaward structure line in the vicinity. The data are plotted in Figure 2.12 along with the recommended minimum FEMA volume of 20 cy/ft. The differences in volume track like the overall profile volumes to −24 ft with minima centered along the reach. The majority of stations do not have 20 cy/ft seaward of the dune crest. However, much higher volumes exist seaward of most structure lines.

In the Buxton area, stations with significant dune volume deficits in the foredune extend from station 1880+63 (near the north village line) to station 1950+63 (~0.5 mile south of old Cape Hatteras Lighthouse). The average volumes in that 7,000-ft reach were 3.5 cy/ft (from dune crest) and 5.0 cy/ft (from structure line) in August 2013.

TABLE 2.3. Dune volumes above +8.5 ft NAVD seaward of the foredune crest and the seawardmost structure line in the Buxton area based on August 2013 conditions.

	Unit Volumes above 8.5 ft NAVD (cy/ft)	
Station	Dune Crest	Structure Line
1790+63	15.2	99.0
1800+63	17.2	33.6
1810+63	12.4	39.3
1821+84	28.7	69.5
1830+63	27.3	39.7
1840+63	21.4	55.1
1850+63	16.1	47.9
1860+63	18.6	42.4
1870+63	16.1	27.7
1880+63	4.6	18.5
1890+63	3.2	0.0
1900+63	2.4	4.2
1910+63	3.0	12.7
1920+63	0.9	9.5
1928+11	0.5	0.0
1940+63	4.9	4.9
1950+63	8.7	8.7
1960+63	21.1	21.1
1970+63	20.9	20.9
1983+77	11.9	11.9

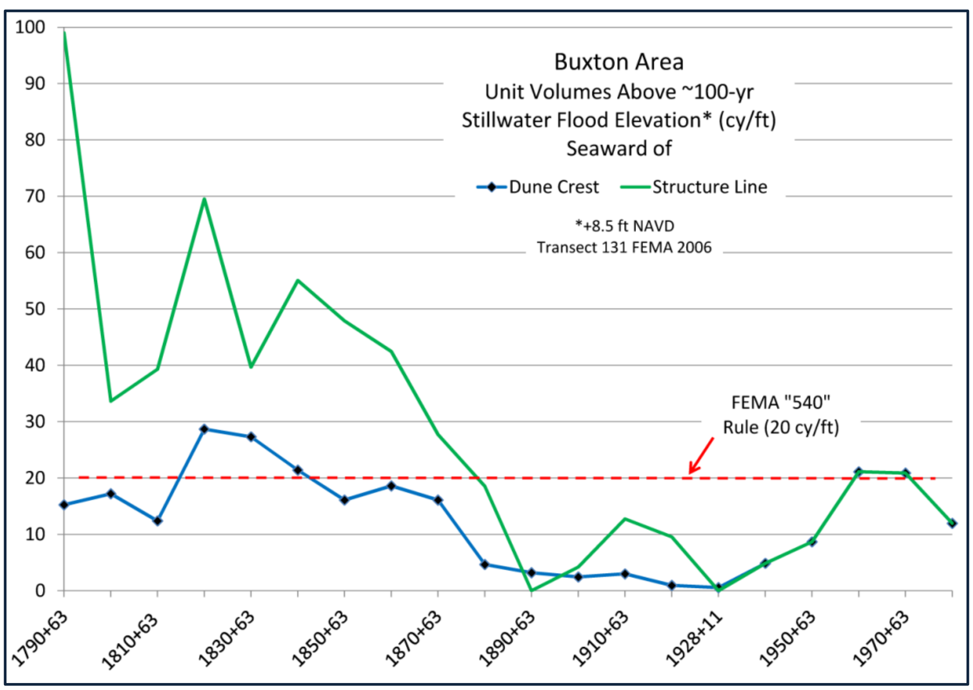


FIGURE 2.12. August 2013 unit volumes in the dunes above 8.5 ft NAVD seaward of the foredune crest and structure line:

2.3.4 Updated Unit Volumes

CSE's profiles from October 2014 extended further north and provide more detail at 500-ft spacing. The volume results, shown in Figure 2.13, confirm the volume minima around stations 1880 to 1930 (5,000 linear feet). A deficit with respect to the 800 cy/ft minimum criteria extends from around 1840 to 1940 (~10,000 ft). The October 2014 data track relatively close to the August 2013 data but are not precisely comparative due to the profile offsets and additional lines surveyed. As planning and design proceed, additional surveys matching the October 2014 dataset will allow confirmation of volume changes over short time periods.

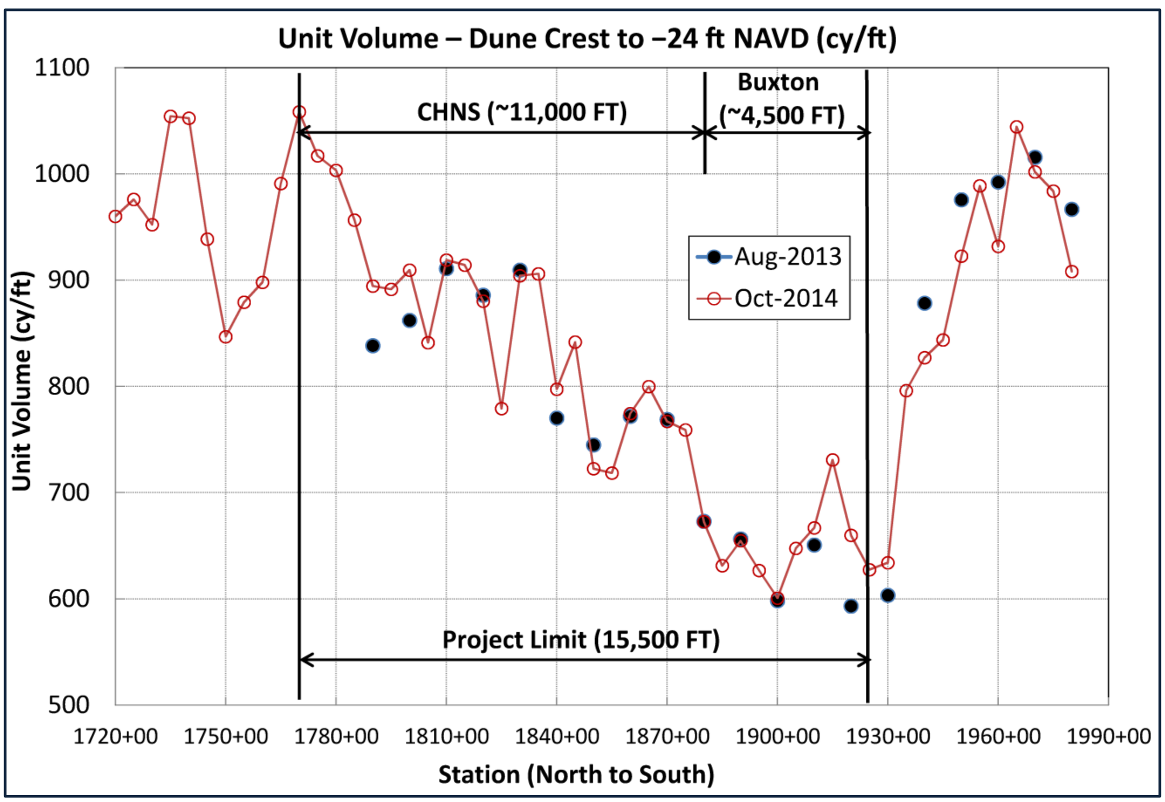


FIGURE 2.13. Variation in unit volume along the Buxton project shoreline between the foredune and −24 ft NAVD. October 2014 data were collected every 500 ft alongshore with profiles offset ~60 ft from the August 2013 data.

2.4 Recommended Minimum Profile Volumes

Based on the preceding profile volume analysis and results in Tables 2.2, CSE adopted certain target minimum profile volumes for Buxton as given in Table 2.4. The adopted values are rounded for convenience and consider volumes seaward of the dune crest as well as some extra volume landward of the dune crest to the seaward structure line. As more data become available, the target profile volumes can be refined.

Table 2.4 indicates there are significant volume deficits averaging of the order ~160–170 cy/ft in the critically eroding section of Buxton. Assuming 5,500 linear feet of shoreline exhibit advanced erosion, deficits of this order total ~880,000–935,000 cy. Viewed another way, nourishment at these levels would be required just to bring the critically eroded sections to the average condition of adjacent beaches. Volumes of this magnitude are larger than the typical Oregon Inlet dredge volume disposed along Pea Island (USACE 2010), but considerably smaller than the recent Nags Head nourishment project (CSE 2011b, Kaczkowski & Kana 2012).

TABLE 2.4. Target unit profile volumes to −24 ft NAVD: (1) from dune crest, (2) from structure line. [*critically eroding sections (see Table 2.2]

BUXTON			
		Average Unit Vol (1)	**Average Unit Vol (2)**
		(cy/ft)	**(cy/ft)**
All Profiles	n=20	803.3	900.2
Upcoast	n=8	829.1	1002.6
Critically Eroding*	n=6	629.2	692.2
Downcoast	n=6	965.7	965.7
Target Minimum		**750.0**	**800.0**
Average Deficit*		**120.8**	**107.8**

As the results for individual profiles show (Table 2.2, Fig 2.10), deficits at some localities with respect to the target volume of 800 cy/ft are as high as 200 cy/ft (eg – station 1900+00 — seaward of the dune crest). Upcoast and downcoast sections tend to be reasonably healthy, although the zone of chronic annual sand losses extends beyond the critically eroded reaches.

The next section evaluates historical erosion and develops estimates of average volumetric erosion rates.

2.5 Historical Erosion Rates

CSE did not locate any recoverable historical profiles encompassing the beach, surf zone, and inshore area to a depth of at least −24 ft NAVD. Lacking such data, a standard method of estimating volumetric erosion rates is by extrapolation from linear rates (CERC 1984).

A long-time rule-of-thumb used by the Corps of Engineers since the first nourishment project at Coney Island (NY) assumes a loss of 1 square foot (ft²) of beach area is roughly equivalent to a loss of 1 cubic yard of sand (CERC 1984). This ratio has also been assumed for some analyses for NCDOT (M Overton, NC State University, pers. comm., October 2013). It can be shown that this ratio varies according to the dimensions of the active zone of profile change but remains constant between fixed contours regardless of foreshore slope (Bruun 1962, Hands 1981, Dean 2002). Normally, the vertical dimension considered extends from the dry-beach elevation to the depth of closure (DOC). For example, if the average height of the dry beach is +7 ft NAVD and the local DOC is −20 ft, there will be 27 cubic feet (cf) contained in 1 ft² of "beach" area (Fig 2.14).

Conveniently, 27 cf equals 1 cy, so the volume (cy) to area (sf) ratio equals 1. This ratio is >1 for beaches that exhibit a deeper DOC and <1 for beaches with a shallow DOC. Figure 2.15 illustrates how the volumetric erosion rate varies with the linear erosion rate as well as the local DOC.

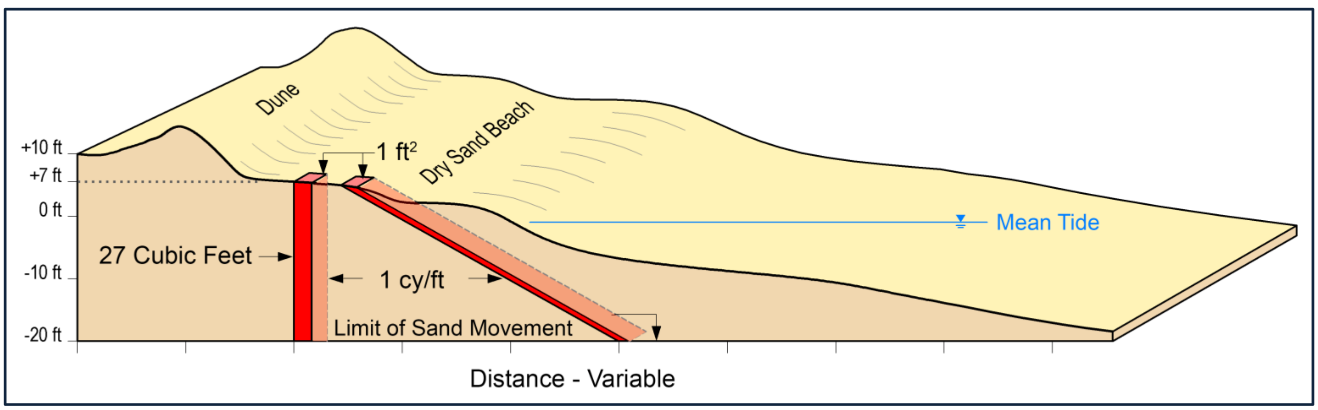


FIGURE 2.14. Volume equivalents on a beach. Example assumes the active beach zone extends from the dry-sand beach elevation at +7 ft to an offshore depth of 20 ft. Therefore, 1 ft² of dry beach area represents ~27 cf of profile volume. This ratio remains constant by simple geometry for a parallelogram with equal end-surface area. This concept can also be used to convert linear shoreline change to equivalent unit volume change. For example, 1 ft of dry beach recession, in this example, is equivalent to 27 cf (per foot of shoreline length) sand loss. 27 cf = 1 cy. The ratio varies with the vertical dimensions of the littoral zone (Bruun 1962, Hands 1981). [After Kana et al 2015]

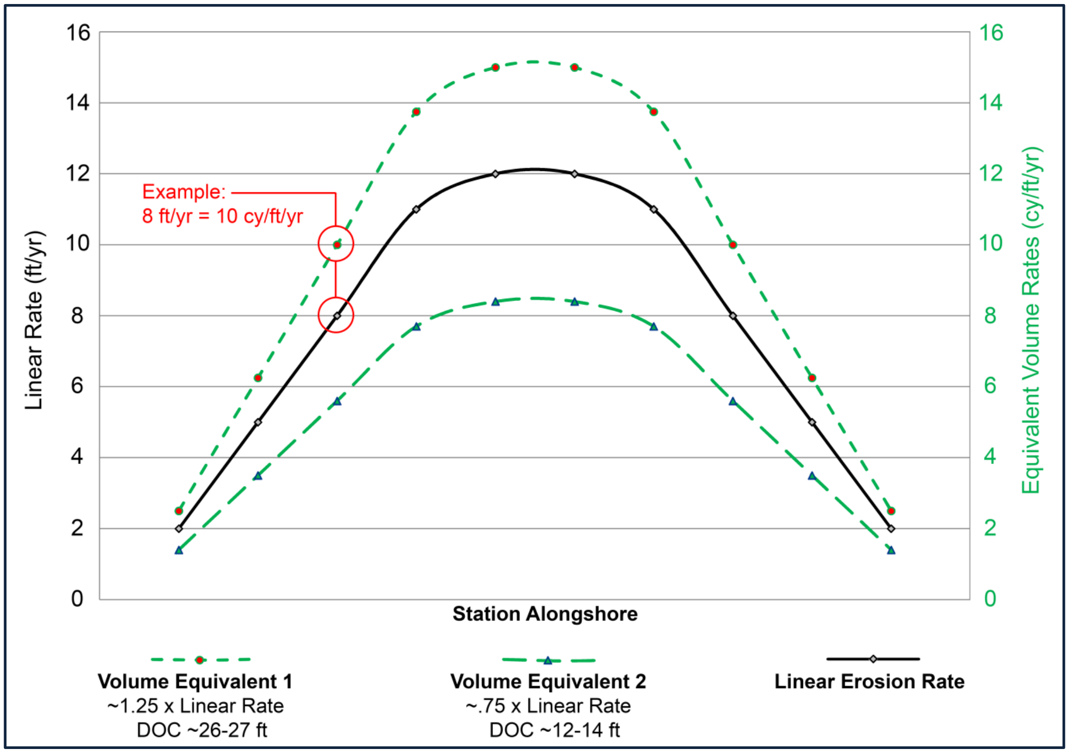


FIGURE 2.15. Example of the relationship between unit volume erosion rate and linear erosion rate for two beaches. The solid line shows a variable linear erosion rate alongshore, much like the trend and magnitudes for Buxton (Source: NCDENR 2012). The upper dashed curve shows an estimated equivalent unit volume erosion rate for high-energy sites with a relatively deep limit of normal sand movement (DOC). The lower dashed curve shows the equivalent volume for a lower-energy site where the DOC is shallower. The ratio that CSE assumed for Buxton is 1.15, based on a DOC ≈ 24 ft NAVD.

At Hunting Island (SC), for example, the inshore area is a relatively constant −12 ft NAVD (defacto DOC) and the dry beach equilibrates around +7 ft. This means 1 ft² of area loss on the visible beach equates to about 0.7 cy of volume loss [ie (7+12)/27 ≈ 0.7]. Similarly, if DOC off Buxton is assumed to be −24 ft NAVD and the average dry-beach elevation is +7 ft NAVD, 1 ft² of beach area loss will equate to about 1.15 cy of volume loss [ie (7+24)/27 ≈ 1.15]. CSE used this latter ratio to convert linear erosion rates to volumetric rates in the project area.*

*[*Overton and Fisher (2005) assumed a similar dry-beach elevation, but a deeper limit of sand exchange (−30 ft MSL) which equates to a ratio of 1.37 (ie – 1 ft of beach widening requires 1.37 cy/ft of nourishment). The authors report that the ratio "…. would need to be refined during the engineering design phase of the beach nourishment project." (pg 7). Their report was prepared prior to the Nags Head project and the availability of post-nourishment profiles into deep water. CSE (2014) reported nearly 100 percent retention of nourishment sand after two years between the foredunes and −19 ft NAVD at Nags Head. Post Irene and Sandy data at Nags Head also show evidence of accretion between −19 ft and −24 ft which significantly exceeds the losses to −19 ft. This implies some onshore transport likely occurred during Irene and Sandy in the zone beyond the −19-ft contour. The ratio assumed by Overton and Fisher (2005) is more conservative, but for the time scales under consideration in the present study, CSE believes a ratio of 1.15 is realistic for planning.]*

2.5.1 *Historical Shorelines*

NCDENR periodically publishes official, long-term, average annual oceanfront erosion rates ("setback factors") for North Carolina. An early analysis was prepared by Tafun et al (1979) who applied the "end-point method," which is retained by NCDENR in recent updates. The end-point method computes average annual rates at each shoreline transect using the earliest and most-current shoreline position. The earliest shorelines considered in prior analyses are typically based on NOAA's National Ocean Service (NOS) "T-sheets" from the 1920s to 1930s. More recent shorelines are interpreted from controlled aerial photography using the "wet/dry" line at the edge of the surf zone, which approximates local MHW at the time of the photography (Overton & Fisher 2003). The most recent update of official shorelines (NCDENR 2012) utilized 1946/49 and July 2009 imagery (end points) from the US Department of Agriculture (USDA). NCDENR (2012) details the various blocking and smoothing algorithms applied in developing the official rates along Dare County. Figure 2.16 shows results of the NCDENR (2012) analysis.

A striking aspect of the NCDENR shoreline change rates along Hatteras Island is their large variation alongshore. Long barrier islands with few active inlets often exhibit more uniform shoreline change rates. This is certainly the case north of Oregon Inlet along most of Bodie Island or along Bogue Banks (NCDENR 2012). By comparison, some short segments of Hatteras Island have zones of moderate accretion (>5 feet per year–ft/yr) in close proximity to zones of high erosion (>10 ft/yr). The Buxton area has been highly erosional, but the rate diminishes in the vicinity of the Cape Hatteras Lighthouse groins. The longest "stable" segment of Hatteras Island is between Salvo and Avon where measured change rates are within a narrow range of 1–5 ft/yr (see Fig 2.16).

CSE obtained the "shape files" of shorelines developed by NCDENR or their consultants at NC State University and East Carolina University, and plotted them against the baseline for the present study. CSE also digitized the June 2012 wet/dry line and added it to base maps of Buxton. An earlier shoreline from the mid 1800s is also depicted. Distances from the CSE baseline to the shoreline were measured at CSE profile transects and then used to check shoreline change rates for several intermediate periods. The shorelines are illustrated in Figure 2.17, and the data are tabulated by CSE station in Attachment 4. Figure 2.18 plots selected results for the Buxton project area. The official NCDENR long-term erosion rates (Figs 2.16 & 2.19) show focused high erosion approaching 10 ft/yr in the area north of Buxton Village along the National Seashore. The rates at CSE project profiles (see Fig 2.18) are consistent with NCDENR official rates, but show some interesting variations according to the time period used.

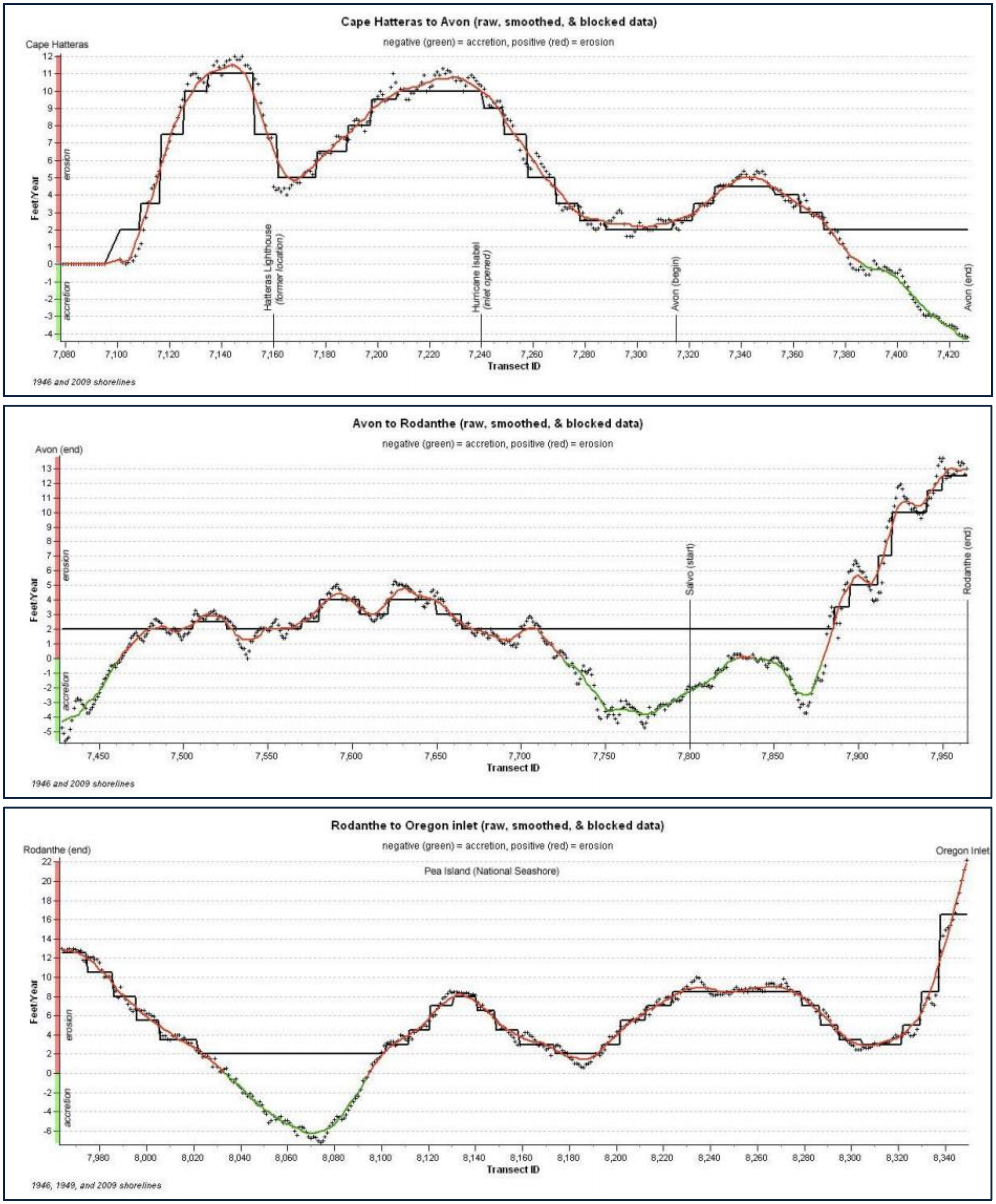


FIGURE 2.16. Long-term shoreline change rates for Hatteras Island derived from historical aerial photography (1946/49 and 2009) showing smoothed and blocked data by transect as prepared by NCDENR/NCDCM and their consultants. [Source: NCDENR 2012, Figs 34-36]

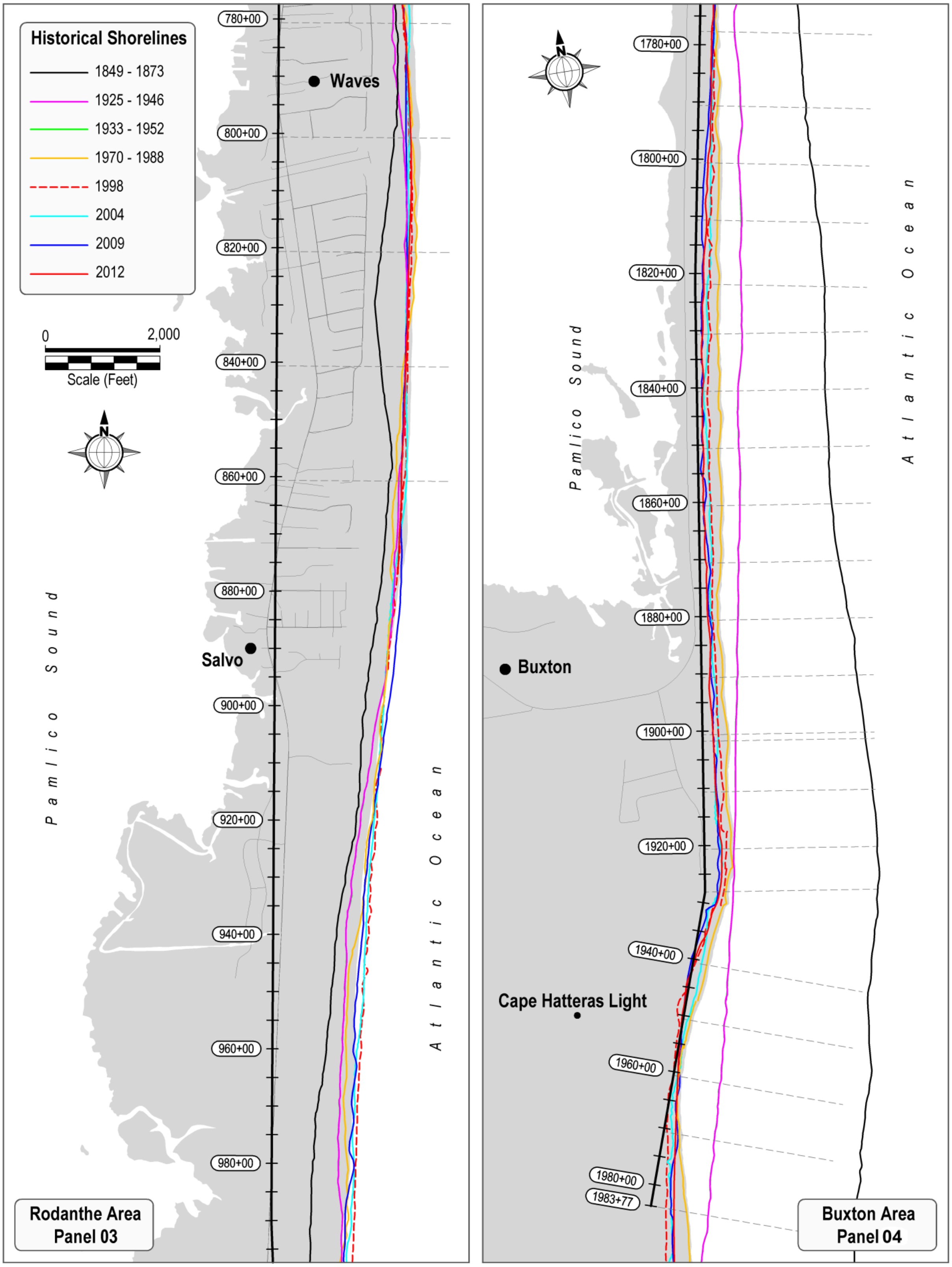


FIGURE 2.17. Historical (approximate MHW) shorelines for Salvo and Buxton from GIS shape files prepared by NCDENR and consultants from NC State University and East Carolina University. The 2012 shoreline (wet/dry line) was digitized by CSE from 2012 imagery. The shoreline "salient" between stations 1920+00 and 1940+00 is associated with groins placed in the 1970s to protect Cape Hatteras Lighthouse (which was eventually moved ~1,600 ft to the southwest). [Courtesy: NCDENR 2012]

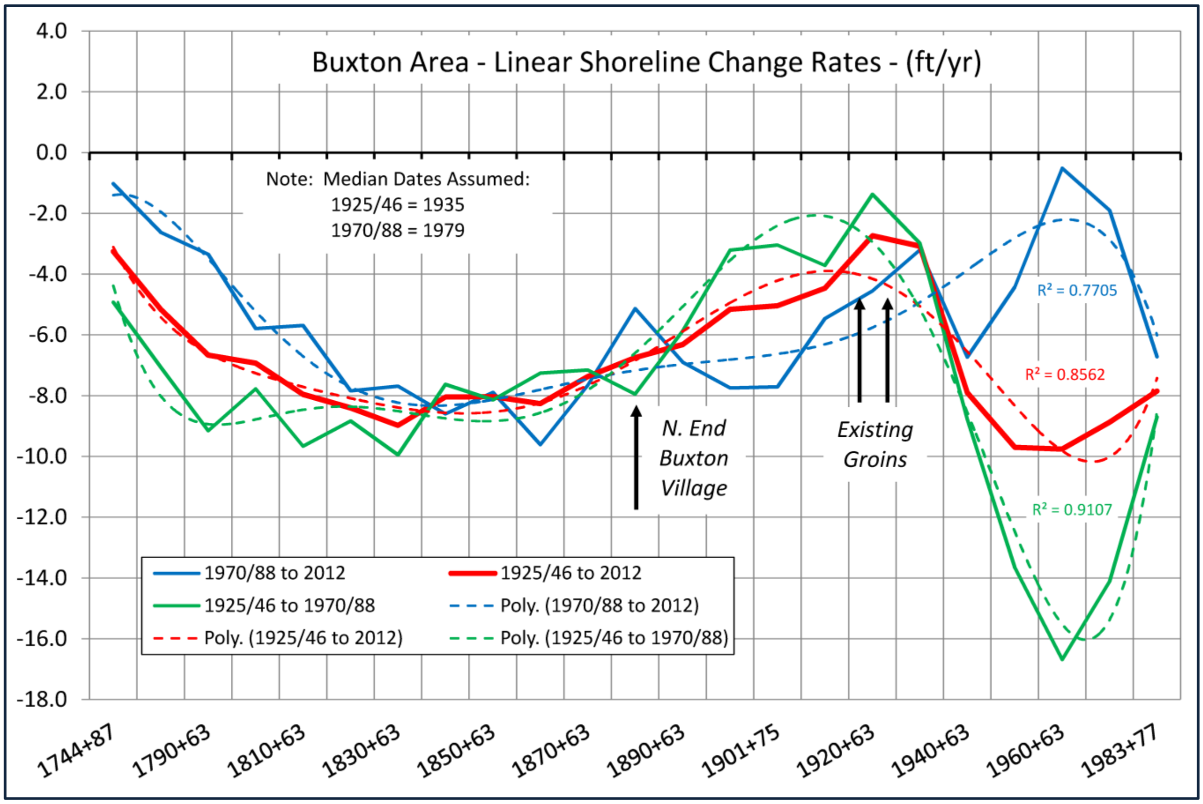


FIGURE 2.18. Linear shoreline change rates (ft/yr) at CSE stations derived from historical shorelines 1920s to 2009, digitized by the State of North Carolina (source: NCDENR 2012). The 2012 shoreline was digitized by CSE from 2012 imagery. [Source: ESRI ArcGIS World Imagery]

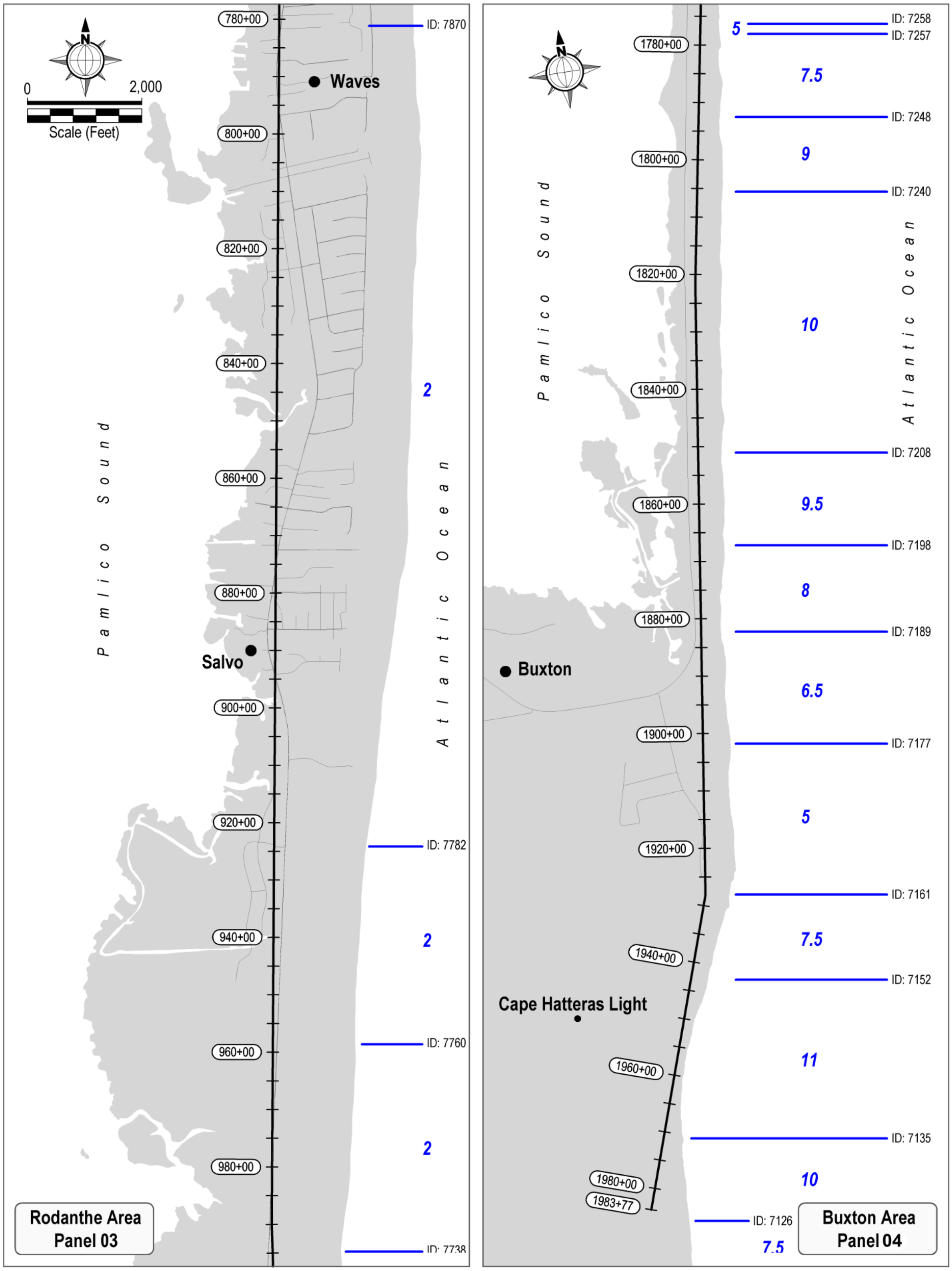


FIGURE 2.19. NCDENR (2012) official shoreline change rates and setback factors (ft/yr) for Salvo and the Buxton project area as published in the most recent update. As Figure 2.16 showed, some segments along Salvo with the minimum "setback factor" of 2 ft/yr are accretional (eg – between transects ID 7738 and 7870). [Source: NCDENR 2012]

The erosion rates in the Buxton project area show long-term maxima around station 1840+00 (~4,000 ft north of the Village of Buxton/National Seashore boundary). Maximum rates are around 9 ft/yr, excluding the area south of the old Hatteras Lighthouse groins. The section of the National Seashore north of Buxton breached in the early 1970s and has washed over Highway NC 12 several times, including as recently as Hurricane *Sandy* in October 2012 (NCDENR 2012, unpublished data).

As Figures 2.16 and 2.18 showed, erosion rates at the groins have been lower than adjacent areas, indicating their stabilizing impact on that portion of the shoreline. Downcoast of the groins, shoreline erosion rates were much greater between 1925/46 and 1970/88 (period generally preceding groin construction) than the period since 1970/88. Some of the reduction in the erosion rate over the past few decades may be related to an ~1.3 million cubic yard nourishment project placed along Buxton in ~1973 (S Rogers, North Carolina Sea Grant, pers. comm., August 2013). For prior beach nourishment data see Cape Hatteras Coastal Engineering Inventory available at https://irma.nps.gov/App/Reference/Profile/2193864 (Dallas et al. 2013).

2.5.2 Equivalent Volumetric Erosion Rates

CSE used official long-term erosion rates published by NCDENR (2012) and determined the rate at each surveyed profile line (Table 2.5). An equivalent volumetric change rate was calculated using the factor 1.15 as discussed in Section 2.4. Table 2.5 lists the estimated average annual volume erosion rates at CSE stations within the project area. The equivalent rates at Buxton range up to 12.6 cubic yards per foot per year (cy/ft/yr) (station 1821+84).

Net annual erosion losses between stations were estimated using the average-end-area method which averages the unit rates for adjacent stations and applies the average over the shoreline distance between stations (see Table 2.5). These subtotals were summed for designated reaches for purposes of estimating net yearly losses in critically eroding areas.

CSE reviewed the locations of profile volume minima (see Section 2.3) and NCDENR linear erosion rates, and delineated two priority reaches along the project area for possible beach restoration. **At Buxton, the critically eroding reaches are considered to be the ~11,500-ft shoreline segment between stations 1805+56 and 1920+63, or an expanded length incorporating the ~13,750-ft segment between stations 1790+63 and 1928+11.**

TABLE 2.5. Official long-term (linear) erosion rates in the Buxton area and the estimated equivalent unit volume erosion rate (cy/ft) using the conversion factor: 1 linear ft = 1.15 cy/ft (see Section 2.5). The net volume rate between profile stations is computed by average-end-area method. [DCM — North Carolina Department of Environment & Natural Resources, Division of Coastal Management]

CSE Station	USACE Station	DCM Transect ID	Distance To Next (ft)	DCM Rate (ft/yr)	Equiv Vol Rate (cy/ft/yr)	Net Vol Rate To Next (cy/yr)
1744+87		7277				
1759+63		7268				
1777+68	N/A	7257		7.5	9.0	—
1790+63				8.0	9.6	—
1792+44		7248	819	9.0	10.8	8,845
1800+63			493	9.0	10.8	5,620
1805+56		7240	507	10.0	12.0	6,084
1810+63			1,121	10.0	12.0	13,788
1821+84	N/A		879	10.5	12.6	10,812
1830+63			1,000	10.0	12.0	12,000
1840+63			1,000	10.0	12.0	11,700
1850+63		7208	1,000	9.5	11.4	11,400
1860+63			667	9.5	11.4	7,204
1867+30		7198	333	8.5	10.2	3,297
1870+63	N/A		1,000	8.0	9.6	9,300
1880+63			143	7.5	9.0	1,244
1882+06		7189	857	7.0	8.4	6,942
1890+63			1,000	6.5	7.8	7,500
1900+63			112	6.0	7.2	739
1901+75		7177	888	5.0	6.0	5,328
1910+63	N/A		1,000	5.0	6.0	5,400
1920+63			748	4.0	4.8	1,795
1928+11		7161		At Terminal Groin		
1940+63						
1950+63						
1960+63						
1970+63	N/A					
1983+77						
Totals	**(1792+44 to 1928+11)**		**13,567**		**9.5**	**128,998**
	(1805+56 to 1920+63)		**11,507**		**10.2**	**114,533**

The northernmost boundary is ~8,750 ft north of Buxton, and the southernmost boundary is situated at the old Hatteras Lighthouse site. **Average annual volumetric erosion rates for these two reaches are estimated to be ~114,500 cy/yr and ~129,000 cy/yr (respectively)** (see Table 2.5). The average annual unit volume erosion rates are 10.2 cy/ft/yr for the most critically eroding reach and 9.5 cy/ft/yr for the expanded reach. In the Buxton area, the highest erosion rate is along CHNS near station 1821+84, ~5,800 ft north of the Village of Buxton, whereas the greatest profile deficit is in the Village of Buxton.

NOTE: For purposes of final design and planning, CSE is evaluating a slightly longer shoreline so as to improve project longevity and provide extended taper lengths for nourishment. The present (2015) plan calls for a maximum project length of 15,500 linear feet in the Buxton area. The minimum project length is assumed to be 11,500 linear feet.

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3.0 COASTAL PROCESSES

Buxton is subject to coastal processes (winds, waves, tides, and currents) typical of the northern North Carolina coast. The Outer Banks in this area is exposed to ocean-swell waves originating from the southeast and storm waves associated with northeasters. Highest waves are generally associated with tropical storms and may occur in phase with hurricane surges. Spring tide range is ~3.5 ft (NOAA-NOS 1994), and tides are semi-diurnal. Previous studies and geomorphic evidence suggest that net longshore transport (ie, sand movement in the littoral zone) is predominantly southerly (Inman & Dolan 1989). This section details littoral processes affecting the proposed project area and addresses certain questions regarding the potential impact of the proposed project on these processes (CERC 1984, Dean 2002).

Use of an offshore borrow area can influence waves, thereby modifying local sand transport rates. Depending on the geometry of the borrow area, the excavation may effectively reduce wave heights in part of the affected area as well as cause wave heights to increase elsewhere. To quantify the changes in waves due to the borrow area and potential impact on sediment transport, wave height over the potential borrow site was analyzed to compare pre-dredge conditions with anticipated post-dredge conditions. Sediment transport was examined to determine how local increases in wave energy density due to the presence of the borrow area might affect the regional sand-transport potential.

The placement of nourishment sand on the beach may potentially impact sediment transport along other strategic locations. Closure depth (the approximate limit of measurable bottom change over particular time scales) was examined in the Buxton area because it is an important consideration in locating the borrow site. It is beneficial for borrow sites to be located offshore of the depth of closure location, so they will be independent of the littoral system normal time scales for planning (ie – decades). Borrow site locations shoreward of the closure depth position may simply shift sediment within the littoral zone and have very little impact on the net sand volume change.

The steady-state spectral wave model (STWAVE) was used in this study to evaluate the changes of wave patterns before and after dredging of the borrow area. The generalized model for simulating shoreline change (GENESIS) was used to evaluate the impact on sediment transport caused by the placement of nourishment sand. Both models are approved by the USACE and have been widely used by coastal engineers and community planners in predicting the behavior of shorelines and sediment transport. Information on each model is available in USACE (2001) and Hanson and Kraus (1989).

3.1 Wave Climate

Offshore wave information is typically obtained from a wave gauge or a global- or regional scale wave hindcast or forecast. Nearshore wave information is required for littoral processes analysis and for the design of almost all coastal engineering projects. Waves drive sediment transport and nearshore currents, induce wave setup and runup, excite harbor oscillations, or impact coastal structures. The longshore and cross-shore gradients in wave height and direction can be as important as the magnitude of these parameters for some coastal design problems.

Two types of wave stations are available offshore of the study area. One is a real-time wave buoy ~16 miles offshore with 12 years of wave records, and the other is a hindcast wave station located ~10.5 miles offshore with 33 years of records.

3.1.1 Real-Time Wave Buoy – Station 41025

Station 41025 at Diamond Shoals (NC), owned and maintained by the National Data Buoy Center (NDBC), appears to be the closest real-time wave buoy to the Buxton project site. The station is located at 35.006 N 75.402 W, ~16 miles southeast of Cape Hatteras (Fig 3.1). The water depth at the station is ~225 ft. This station has recorded wind and wave data since 2003; however, there were no wave direction records until 2012. The wave height, period, and direction analyses based on available data are listed in Table 3.1. It shows that June, July, and August have the lowest wave heights compared to other months.

FIGURE 3.1. Station 41025 at Diamond Shoals (NC), owned and maintained by the National Data Buoy Center (NDBC), appears to be the closest real-time wave buoy to the Buxton project site. The station is located at 35.006 N 75.402 W, ~16 miles directly offshore of Cape Hatteras (NC).

TABLE 3.1. Monthly average wave climate from 2003 through 2014 at NDBC wave buoy station 41025 at Diamond Shoals (NC). [Source: NDBC] [*Wave direction uses meteorological convention. A direction of 0° corresponds to a wave arriving from True North. Similarly, a direction of 90° corresponds to a wave from due east. Wave direction records are available only for the period between 2012 and 2014 at this station.]

	12-Year Record (2003-2014) at Diamond Shoals		
	Wave Height (ft)	**Wave Period (s)**	**Wave Direction***
January	5.61	5.20	107.5
February	5.70	5.31	110.1
March	6.03	5.58	166.2
April	5.59	5.39	87.6
May	4.53	5.14	132.2
June	3.68	4.78	133.4
July	3.76	4.83	153.1
August	3.58	5.21	124.3
September	5.51	5.86	94.7
October	4.88	5.36	102.2
November	5.51	5.42	107.0
December	5.50	5.29	105.2
Average	**5.00**	**5.28**	**118.6**

3.1.2 Wave Information Studies – Station 63230

The Wave Information Studies (WIS) is a project sponsored by US Army Corps of Engineers (USACE) that generates consistent, hourly, long-term (20+ years) wave climatology along all US coastlines, including the Great Lakes and US island territories. Unlike a forecast, a wave hindcast predicts past wave conditions using a computer model and observed wind fields. By using value-added wind fields, which combine ground and satellite wind observations, hindcasted wave information is generally of higher accuracy than forecast wave conditions and is often representative of observed wave conditions. Hindcast data available from each site include hourly wind speed, wind direction, bulk wave parameters (significant wave height, period, and direction), as well as discrete directional wave spectra at 1- to 3-hour intervals. WIS wave direction uses meteorological convention. A direction of 0° corresponds to a wave arriving from true north. Similarly, a direction of 90° corresponds to a wave from due east.

The closest WIS station to the project site is station 63230. It is located ~10.5 miles due east of Buxton at 35.25° N and -75.33° W in water depth of ~60 ft (see Fig 3.1 for location). This station has hindcast data for 33 years between 1980 and 2012. Figure 3.2 is a polar histogram of the frequency of occurrence of wave directions based on the 33-year record, and Table 3.2 lists percent occurrence of wave height and period by directions. The majority of waves (88.5 percent) are from northeast to south (45°–180°), but the northerly waves are generally larger than those from other directions. Waves coming from the 45° band from east, east-southeast to southeast (ie – 90° to 135° band) occur 45 percent of the time, and waves coming from southeast have the highest occurrence of 16.2 percent compared to the other directions.

The series of graphics in Figure 3.3 show the monthly polar histograms of wave directions and wave heights. In late spring and summer months between May and August, waves are mainly from the southeast with most wave heights smaller than 1 m (~3 ft), and the rest of the year waves are mainly from northeast to east with most wave heights between 1 and 2 m (~3 and ~6 ft). The extreme wave conditions were analyzed at WIS station 63230, linearly fit for the top 21 events, and used to extrapolate 50-year and 100-year return-period events of 7.8 m (~25.6 ft) and 8.2 m (~29.6 ft) (respectively) (Fig 3.4).

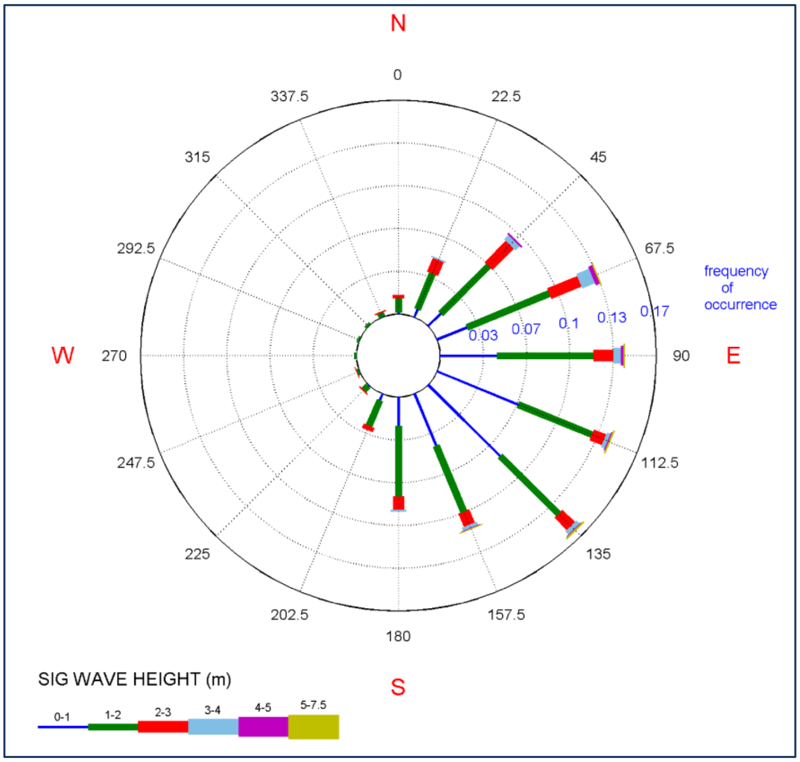


FIGURE 3.2.

Wave rose of WIS station 63230 showing the occurrence frequency of wave direction and wave height based on the 33-year record between 1980 and 2012. [Source: USACE WIS]

TABLE 3.2. Percentage of occurrence of wave directions in 16 bands with 22.5° increment, associated wave heights (in meters) and wave periods (seconds). Note: Buxton shore-normal is ~98° from true north. [Source: USACE-WIS] [*Wave direction uses meteorological convention. A direction of 0° corresponds to a wave arriving from true north. Similarly, a direction of 90° corresponds to a wave from due east.]

Direction from °True	33-Year Record (1980-2012) at WIS 63230		
	Percentage of Occurrence (%)	Mean Wave Height (ft)	Mean Wave Period (s)
0 ± 11.25	1.5	5.25	6.9
22.5 ± 11.25	4.9	5.25	7.4
45 ± 11.25	9.6	5.58	8.3
67.5 ± 11.25	13.4	5.91	9.3
90 ± 11.25	14.3	4.92	9.6
112.5 ± 11.25	14.5	3.94	9.4
135 ± 11.25	16.2	3.94	9.2
157 ± 11.25	11.5	4.27	8.0
180 ± 11.25	9.0	4.59	6.9
202.5 ± 11.25	3.1	4.59	6.6
225 ± 11.25	0.6	4.59	6.7
247.5 ± 11.25	0.2	4.59	6.8
270 ± 11.25	0.2	4.59	6.7
292.5 ± 11.25	0.2	4.92	6.8
315 ± 11.25	0.2	4.92	6.6
337.5 ± 11.25	0.5	4.92	6.8
All Directions	100	4.59	8.6

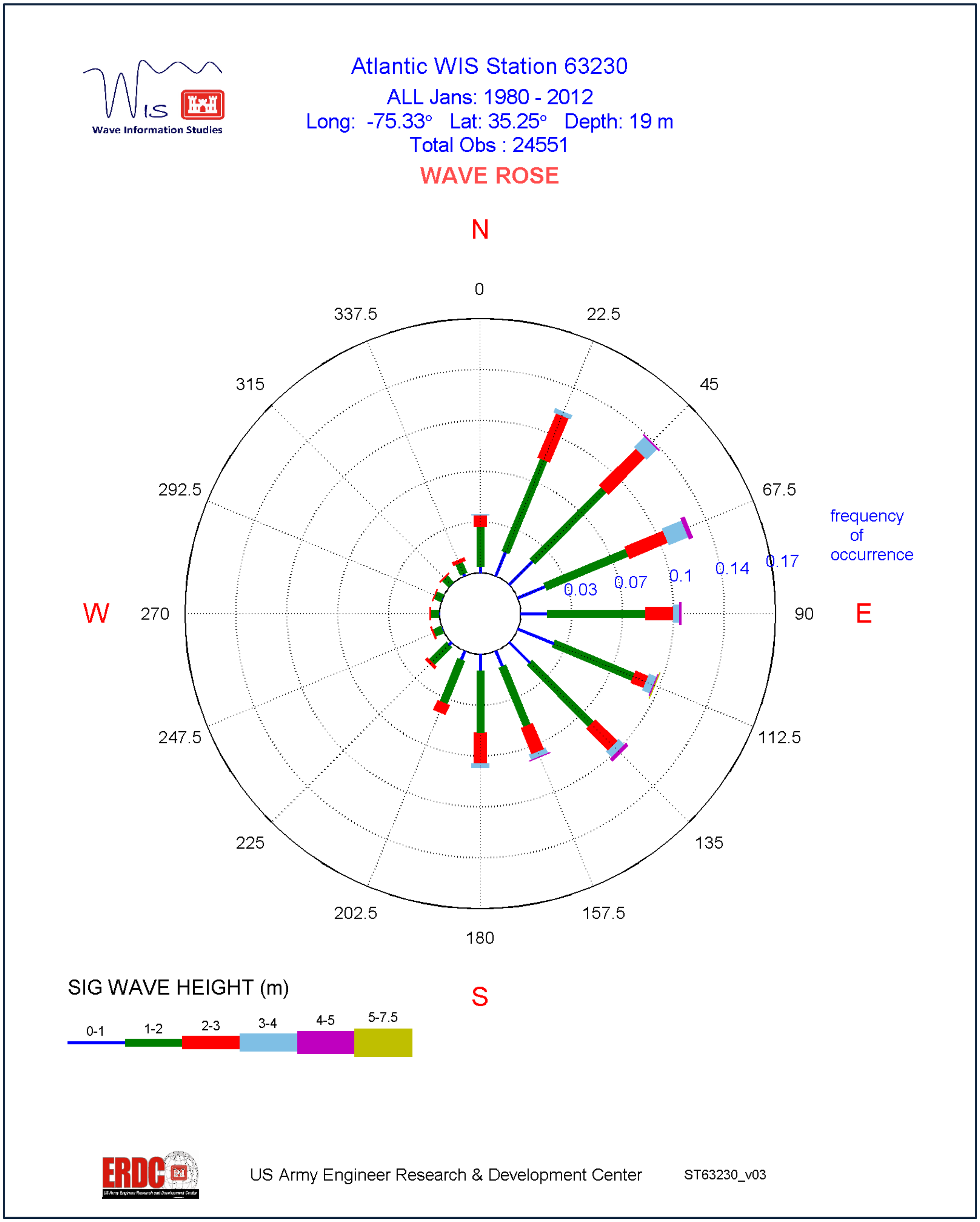


FIGURE 3.3. January — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

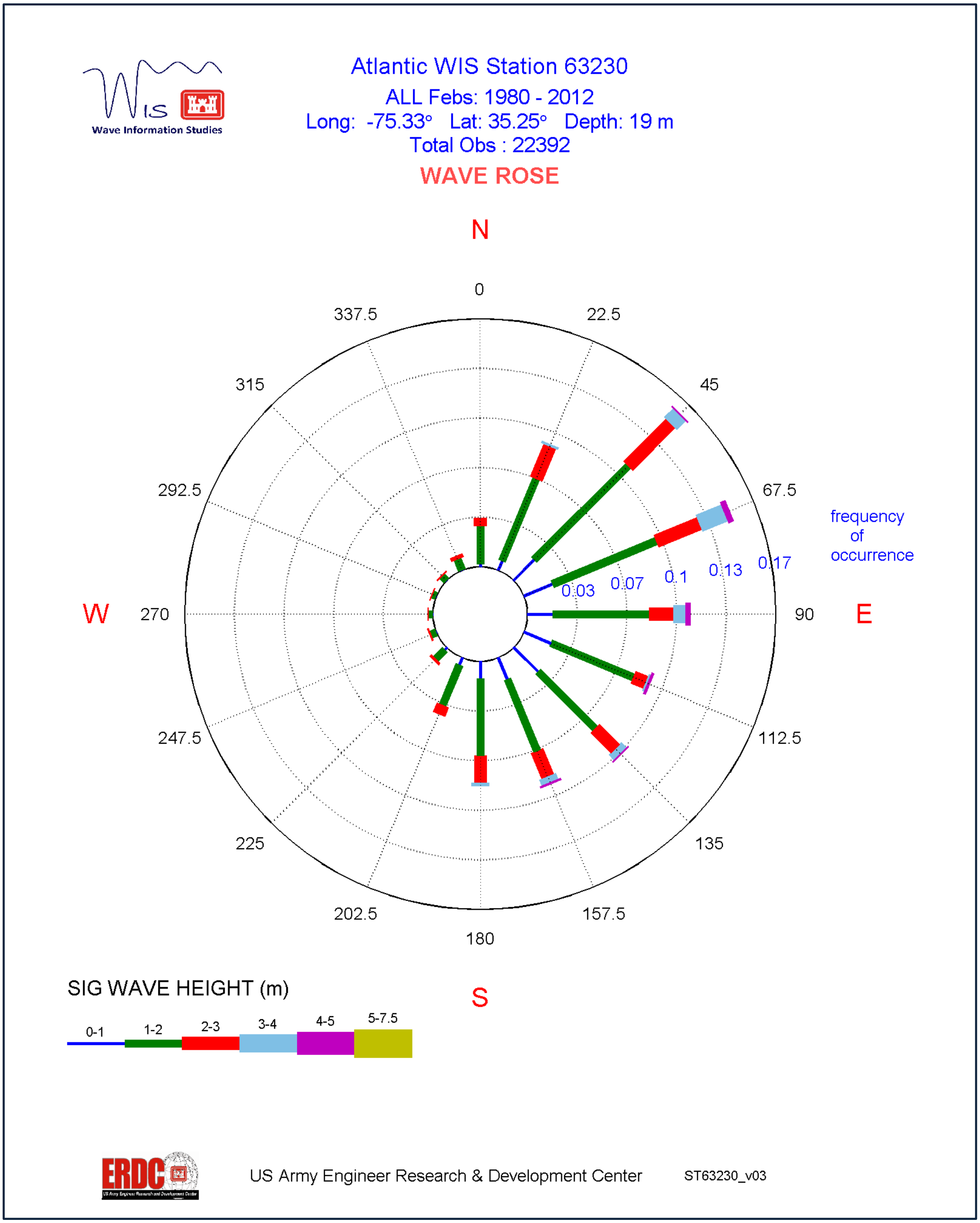


FIGURE 3.3. February — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

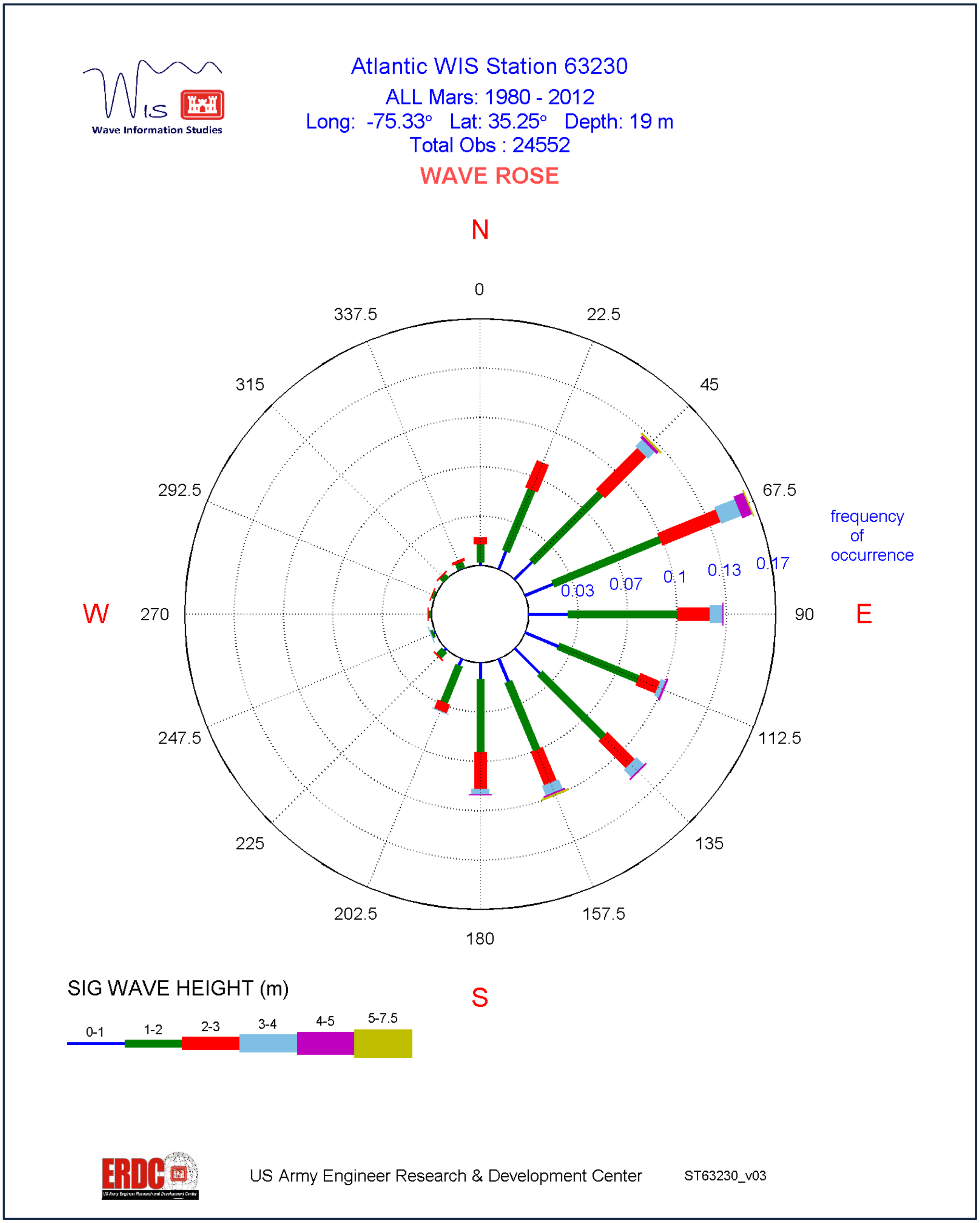


FIGURE 3.3. March — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

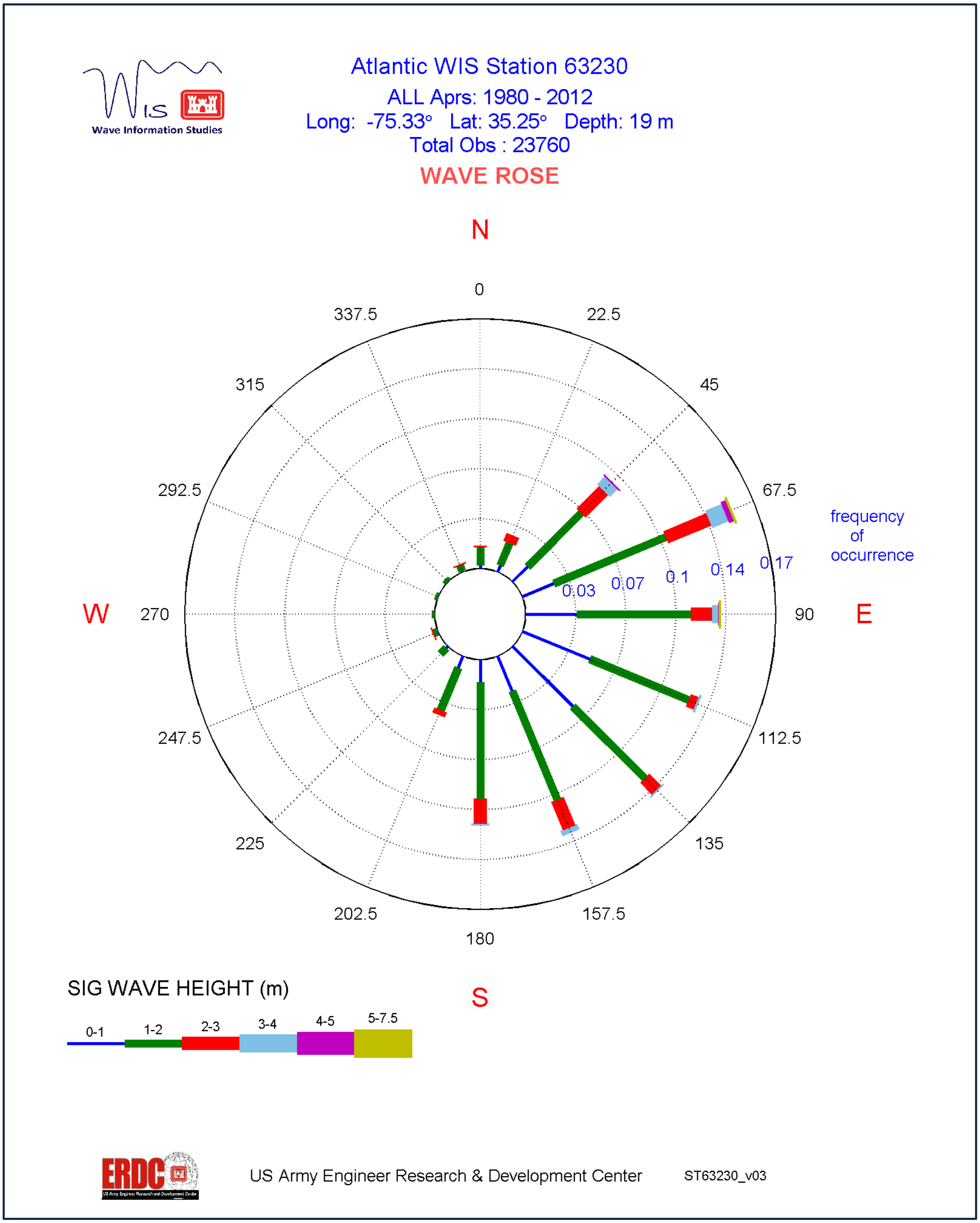


FIGURE 3.3. April — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

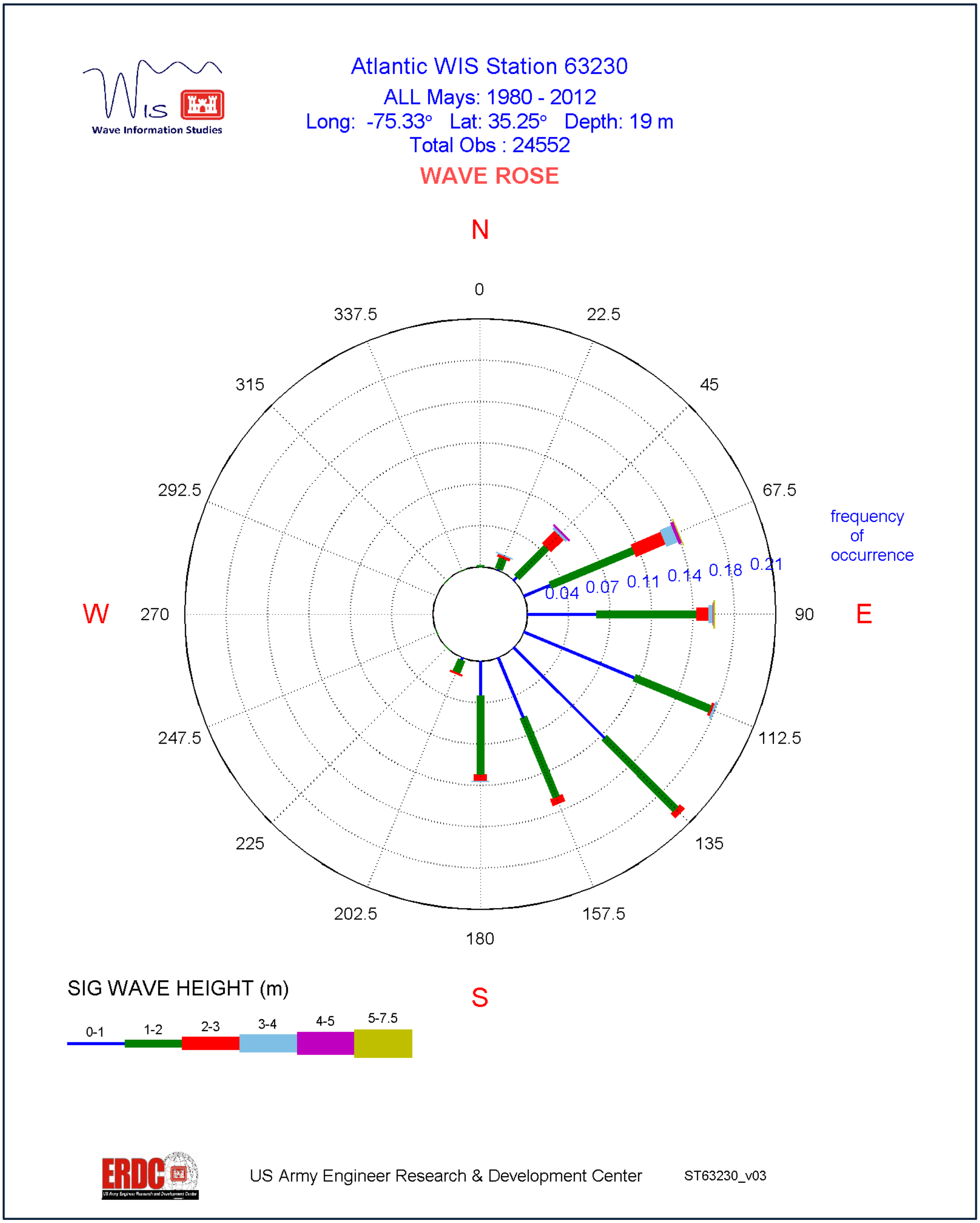


FIGURE 3.3. May — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

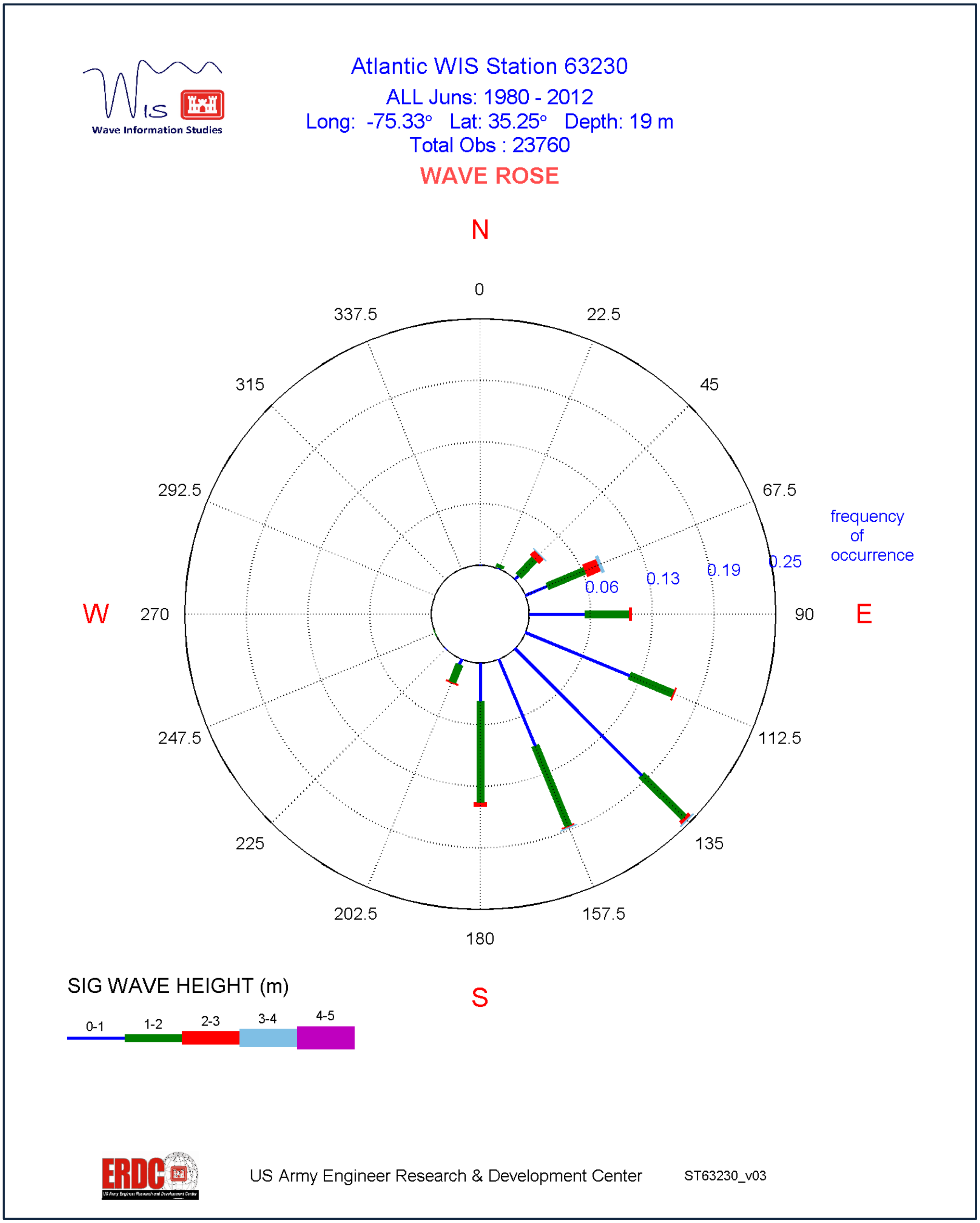


FIGURE 3.3. June — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

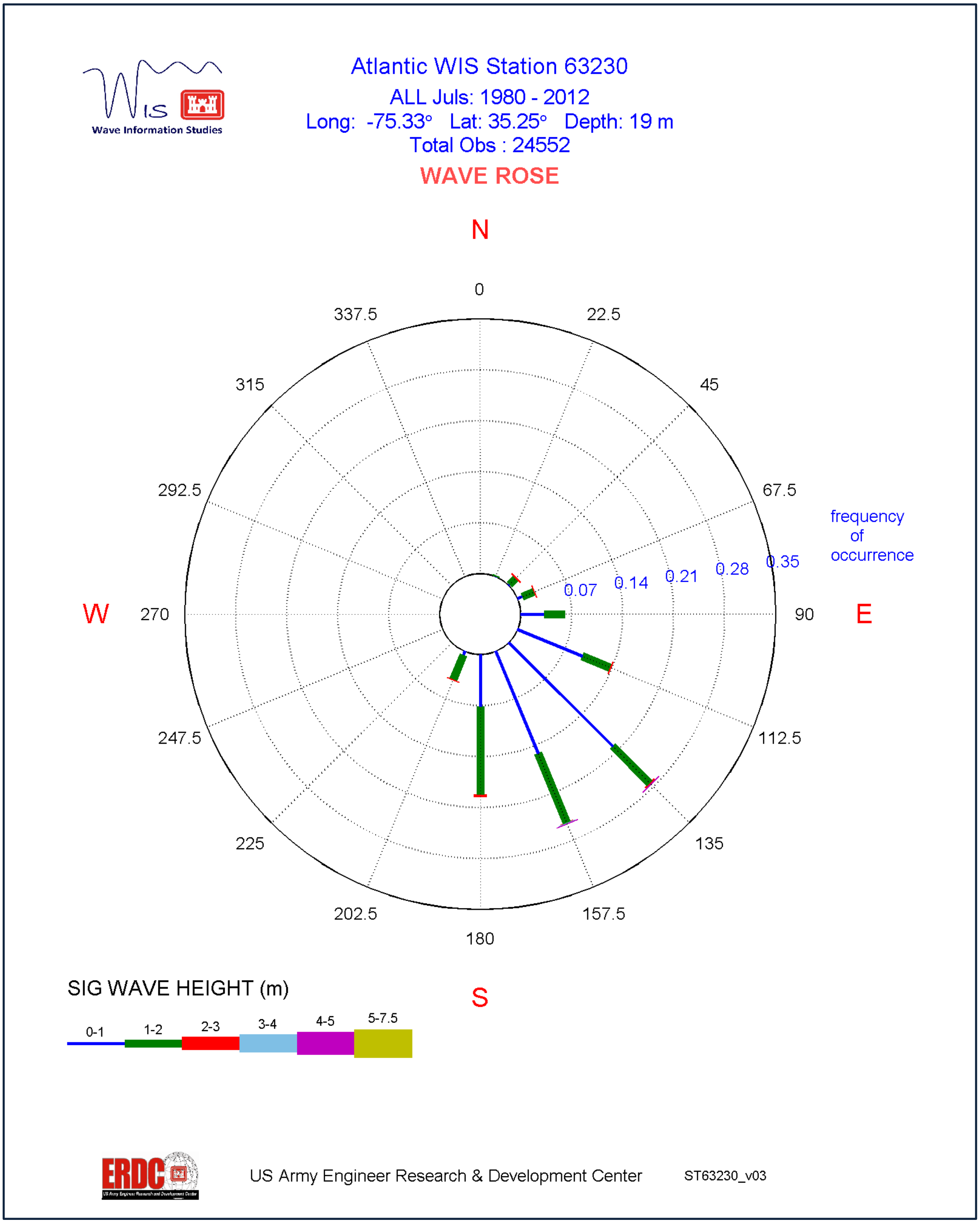


FIGURE 3.3. July — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

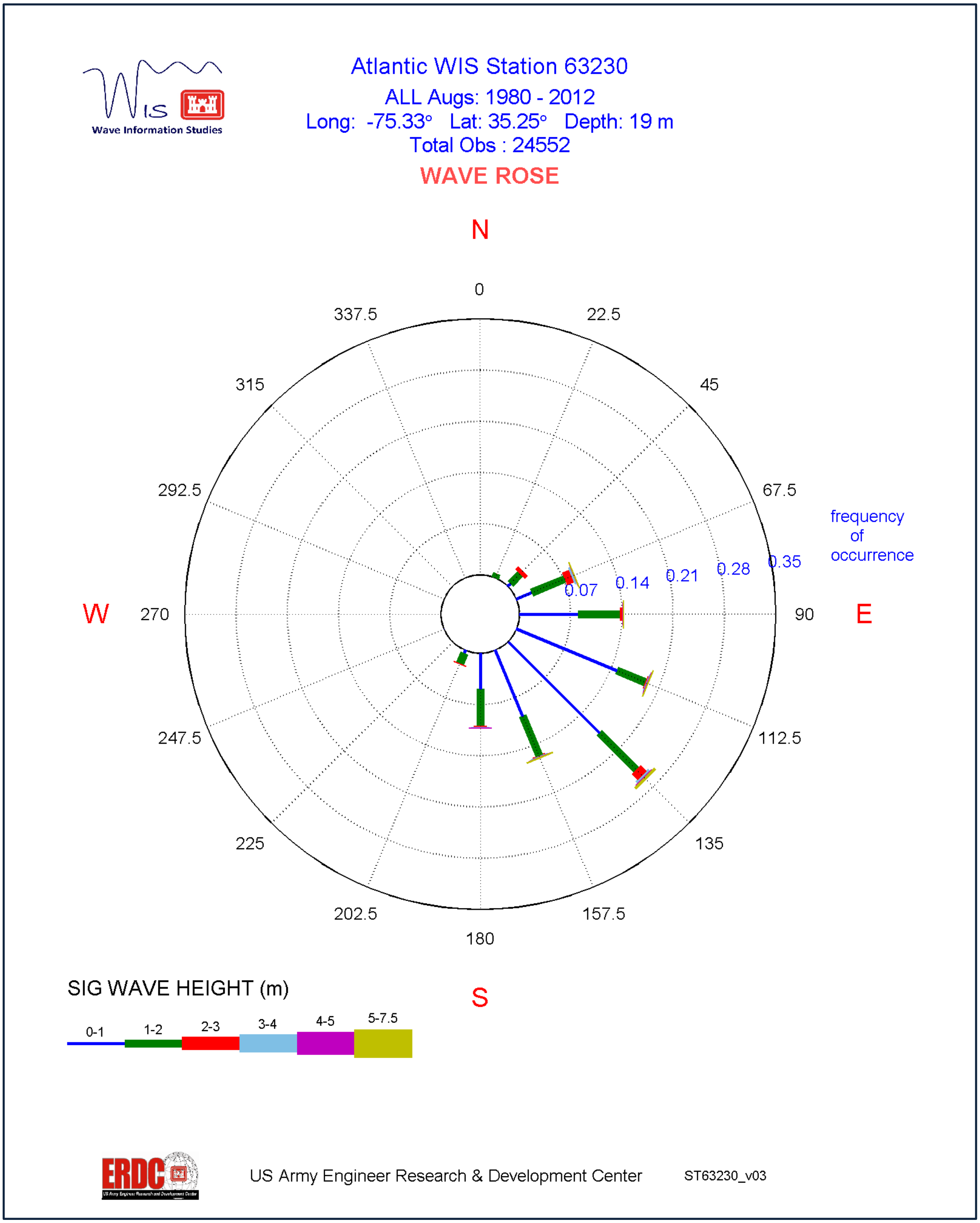


FIGURE 3.3. August — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

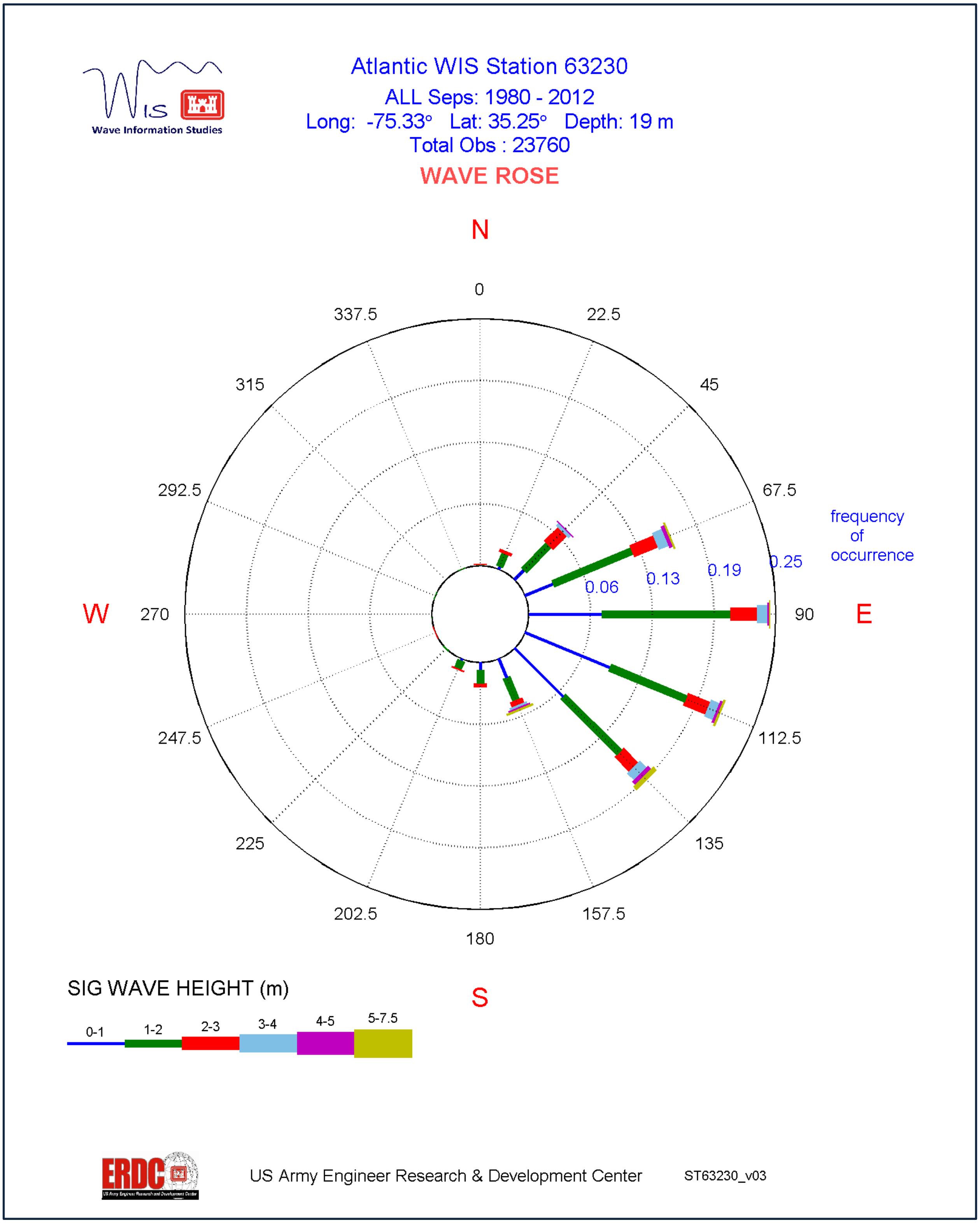


FIGURE 3.3. September — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

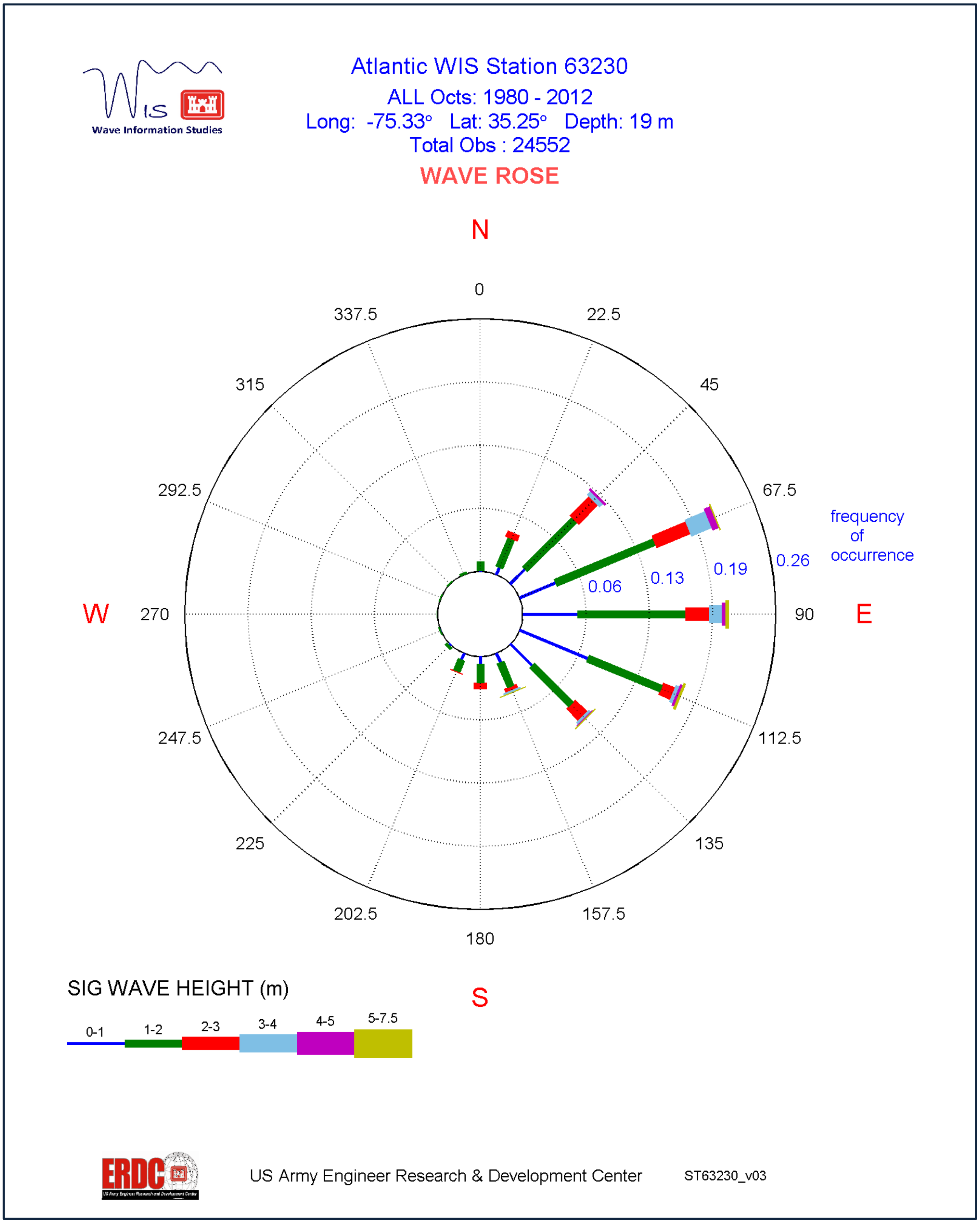


FIGURE 3.3. October — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

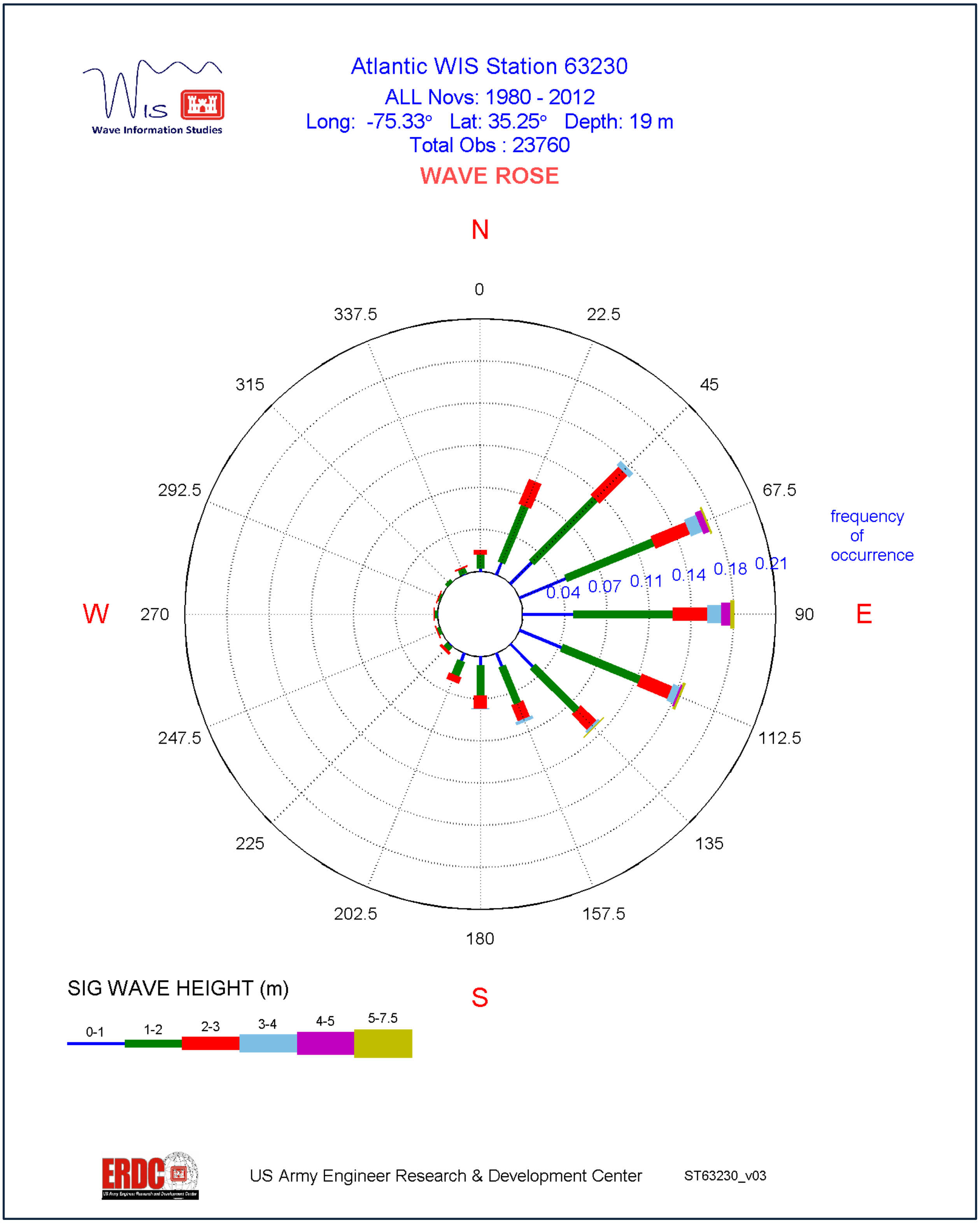


FIGURE 3.3. November — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

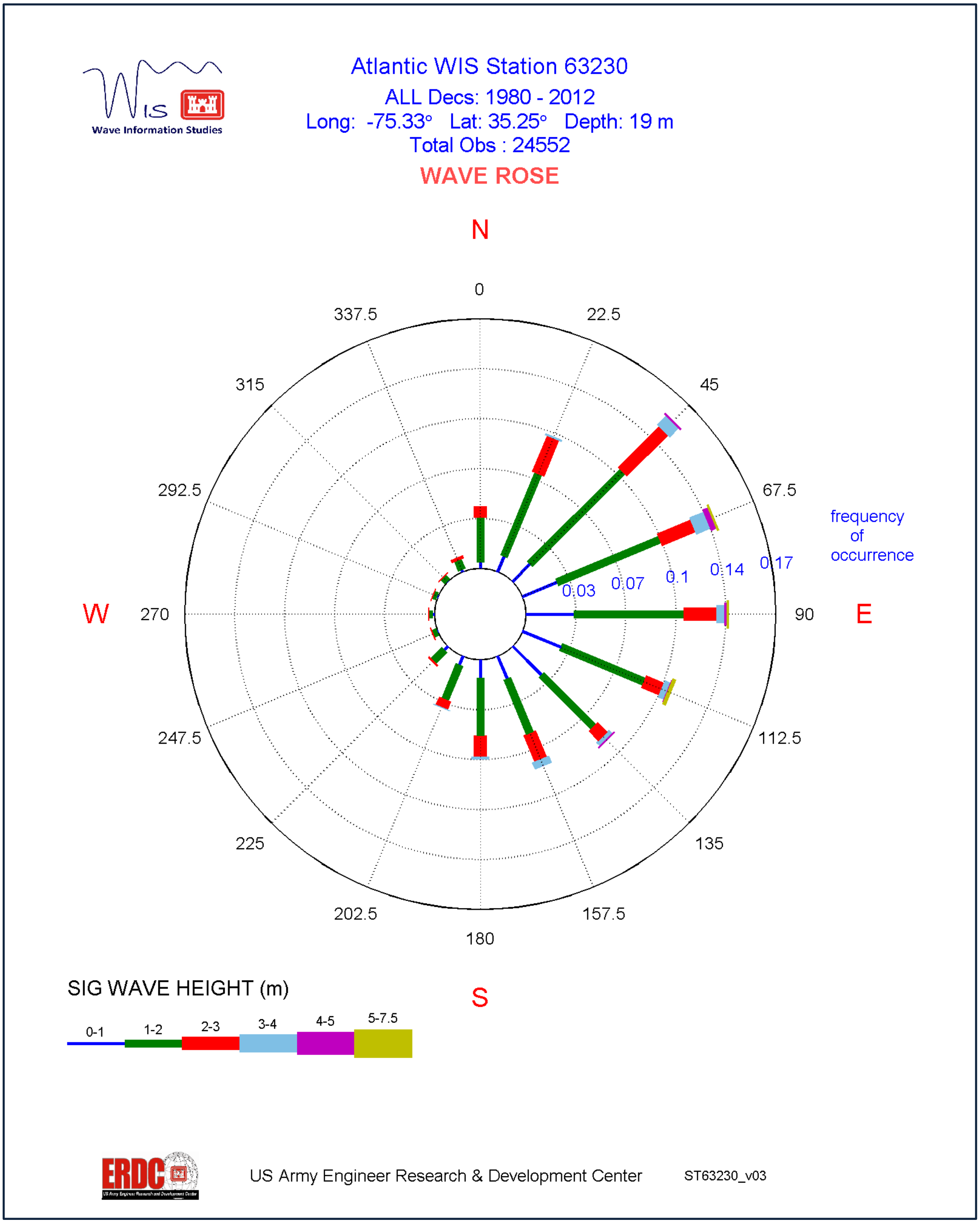


FIGURE 3.3. December — Monthly wave rose of WIS station 63230 showing the frequency of occurrence of wave direction and wave height each month based on the 33-year record between 1980 and 2012.

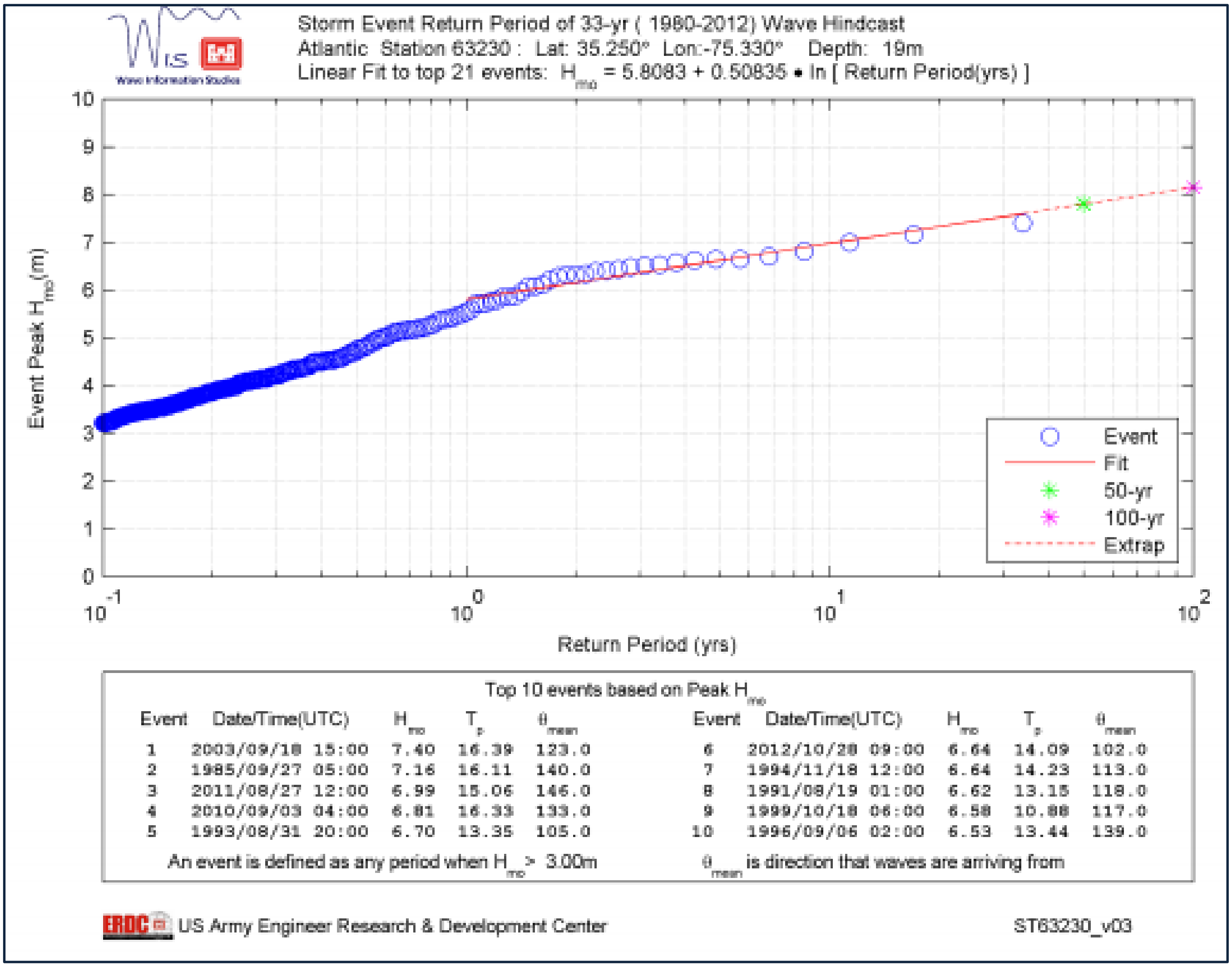


FIGURE 3.4. Peak wave heights of storm events over 33 years (1980–2012) based on wave hindcasts at station 63230. The linear trend of the highest 21 wave events was used to extrapolate 50-year and 100-year return-period storm-wave heights for the Buxton offshore area.

3.2 Wave Modeling

3.2.1 Model Capabilities

The purpose of applying nearshore wave transformation models is to quantitatively describe the change in wave parameters (wave height, period, direction, and spectral shape) between the offshore and the nearshore (typically depths of 40 meters (120 ft) or less]. In relatively deep water, the wave field is fairly homogeneous on the scale of kilometers; but in the nearshore, where waves are strongly influenced by variations in bathymetry, water level, and currents, wave parameters may vary significantly on a scale of tens of feet.

STWAVE is an easy-to-apply, flexible, robust, half-plane model for nearshore wind/wave growth and propagation (USACE 2001). STWAVE simulates depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, parametric wave growth because of wind input, and wave-wave interaction and white capping that redistribute and dissipate energy in a growing wave field.

A wave spectrum is a statistical representation of a wave field. Conceptually, a spectrum is a linear superposition of monochromatic waves which describes the distribution of wave energy as a function of frequency (one-dimensional spectrum) or frequency and direction (two-dimensional spectrum). The peak period of the spectrum is the reciprocal of the frequency of the peak of the spectrum. The wave height (significant or zero-moment wave height) is equal to four times the square root of the area under the spectrum. STWAVE is based on the assumption that the relative phases of the spectral components are random, and thus phase information is not tracked (ie – it is a phase-averaged model).

In practical applications, wave-phase information throughout a model domain is rarely known accurately enough to initiate a phase-resolving model. Typically, wave-phase information is only required to resolve wave-height variations near coastal structures for detailed, near-field reflection and diffraction patterns. Thus, for these situations, a phase-resolving model should be applied. For the Buxton nourishment plan (ie – comparison of pre- and post-dredging wave patterns and determination of relative impacts of the proposed project), STWAVE has proven to be sufficient (Ekphisutsuntorn et al 2010, Kuang 2010, Kaczkowski & Kana 2012).

3.2.2 Model Assumptions

The typical assumptions made in the STWAVE model are:

a) *Mild bottom slope and negligible wave reflection*. STWAVE is a half-plane model, meaning that wave energy can propagate only from the offshore toward the nearshore (±87.5° from the x-axis of the grid, which is typically the approximate shore-normal direction). Waves reflected from the shoreline or from steep bottom features travel in directions outside this half plane and thus are neglected. Forward-scattered waves (eg – waves reflected off a structure but traveling in the +x direction) are also neglected.

b) *Spatially homogeneous offshore wave conditions.* The variation in the wave spectrum along the offshore boundary of a modeling domain is rarely known, and for domains on the order of tens of kilometers, is expected to be small. Thus, the input spectrum in STWAVE is constant along the offshore boundary.

c) *Steady-state waves, currents, and winds.* STWAVE is formulated as a steady-state model. A steady-state formulation reduces computation time and is appropriate for wave conditions that vary more slowly than the time it takes for waves to transit the computational grid. For wave generation, the steady-state assumption means that the winds have remained steady sufficiently long for the waves to attain fetch-limited or fully developed conditions (waves are not limited by the duration of the winds).

d) *Linear refraction and shoaling.* STWAVE incorporates only linear wave refraction and shoaling, thus does not represent wave asymmetry. Model accuracy is therefore reduced (wave heights are underestimated) at large Ursell numbers.

e) *Depth-uniform current.* The wave-current interaction in the model is based on a current that is constant through the water column. If strong vertical gradients in current occur, their modification of refraction and shoaling is not represented in the model. For most applications, three-dimensional current fields are not available.

f) *Bottom friction is neglected.* The significance of bottom friction on wave dissipation has been a topic of debate in wave-modeling literature. Bottom friction has often been applied as a tuning coefficient to bring model results into alignment with measurements. Although bottom friction is easy to apply in a wave model, determining the proper friction coefficients is difficult. Also, propagation distances in a nearshore model are relatively short (tens of kilometers), so that the cumulative bottom friction dissipation is small. For these reasons, bottom friction is neglected in STWAVE.

g) *Linear radiation stress.* Radiation stress is calculated based on linear wave theory.

The governing equations and other aspects of the model can be found in the USACE's (2001) technical report.

3.3 Shoreline Evolution Modeling

GENESIS was used in this study to evaluate longshore sediment transport during various stages of the design life following the beach nourishment project. Results were used to evaluate the impact of the proposed nourishment and borrow-area dredging on longshore transport at the beach.

GENESIS is designed to simulate long-term shoreline changes at coastal engineering sites resulting from spatial and temporal differences in longshore sediment transport (Hanson & Kraus 1989). The longshore extent of the modeled reach can range from <1 mile to 50 miles, and simulation time periods can range from 1 month to 10 years. The shoreline evolution portion of the numerical modeling system is based on one-line theory, which assumes that the beach profile shape remains unchanged. This allows shoreline change to be described uniquely in terms of the translation of a single point on the profile. [See for example, MHW shoreline, or National American Vertical Datum of 1988 (NAVD 88) shoreline for this study.]

The structure of GENESIS was originally developed by Hanson (1987) in a joint research effort between the University of Lund (Sweden) and the Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES). It has been tested, revised, and upgraded since it was developed and has been widely used by coastal engineering and planning communities for predicting the behavior of shorelines and long-shore transport. Project sites include stretches of coast in the United States such as Alaska, California, Louisiana, New Jersey, New York, Texas, Florida, and the Carolinas. Additionally, there are applications along the coastlines outside of the United States in countries such as Sweden, Japan, Thailand, and China (Horikawa & Hattori 1987, Hanson et al 1989, Beumel & Beachler 1994, Bodge et al 1996, Ebersole et al 1996, ERDC 2005, Ravens & Sitanggang 2007, ACRE 2008, Juh 2008, Ekphisutsuntorn et al 2010, Kuang 2010, Kaczkowski & Kana 2012).

The GENESIS model (Hanson & Kraus 1989) is the major numerical model of beach nourishment planform evolution and was introduced by Dr. Robert Dean of University of Florida in his text book *Beach Nourishment, Theory and Practice* (2002). It has been described as *"a must for nourishment designers and a starting point for coastal scientists interested in nourishment performance"* (reviewed by Marcel Stive, Chair of Coastal Engineering, Delft University of Technology). Several project examples using this model are analyzed in the book. As concluded by Dean (2002) and also addressed in numerous articles in the coastal engineering literature, several key factors should be taken into consideration to have a successful application of the model. They are listed below.

- Representative wave data or reliable hindcasts are available.
- Historical shoreline position and the longshore distribution of volume changes for substantial periods are available.
- Proper calibration and verification of model.
- Appropriate model setup including domain coverage, grid size and actual bathymetry.
- An external wave transformation model having the capability to transform the wave data from offshore to the reference point as required by the GENESIS model.

When the GENESIS model was used for the Buxton project, the above-listed key factors were satisfied, except there was no historical shoreline position for model calibration or verification. Historic annual erosion rates determined from the previous sections of this report were used to calibrate the sediment-transport model. Consequently, the model results were not used to evaluate shoreline evolution, but rather the relative impact of the proposed project on longshore sediment transport.

The wave-energy field required by the GENESIS model was provided by a numerical wave model, STWAVE, which was first applied to transform representative offshore waves to the reference point having a near-breaking depth. The internal wave-transformation model within GENESIS was then used to mathematically model wave propagation from the reference point to the breaking point and to the beach. This internal model determined the breaking wave characteristics which were used to calculate the actual longshore sediment transport.

The models (STWAVE and GENESIS) were executed within the Coastal Engineering Design & Analysis System (CEDAS) (V4.03, available from Veri-Tech Inc) software package. The CEDAS software allows direct coupling of the STWAVE model and the GENESIS model (ie – the wave energy field calculated from STWAVE was used directly by GENESIS for calculating shoreline changes and sediment transport).

In the following sections, the details of model setup, applications for beach nourishment design templates, and the environmental impact of the proposed dredging and nourishment will be discussed. The conclusions of the engineering study will be given after the discussion. A brief outline of each section is listed below:

Section 3.4)	STWAVE and GENESIS model setup including wave climate analysis, model domain setup, bathymetry application, and determination of model parameters
Section 3.5)	STWAVE model results of pre- and post- dredging scenarios
Section 3.6)	GENESIS model calibration on sediment transport rates
Section 3.7)	GENESIS model results to evaluate impact of proposed nourishment and borrow area dredging on longshore transport at the beach
Section 3.8)	Conclusions

3.4 Model Setup

The task of model setup includes determining the computational domain, building up the model grid, designating model parameters, and generating input data files. Input data of a typical STWAVE model and a GENESIS model include the wave field at the offshore boundary (wave height, period, and direction), bathymetry over the model domain, initial shoreline position, measured shoreline position for calibration purposes (if applicable), and coastal engineering activities (coastal structure positions or beach fill characteristics if applicable). The STWAVE model output includes the wave field over the computational domain, and the GENESIS model output includes the shoreline position and longshore transport rates at user-specified time steps.

3.4.1 STWAVE Model Grid

As discussed in previous sections, the proposed project area starts from station 1770+50 and extends southward to station 1925+50, covering a total of ~2.94 miles (15,500 ft) from north to south. An STWAVE grid extends about 1.5 miles beyond the north boundary and 2 miles beyond the south boundary of the project site. Extensions of the model domain beyond the project area ensure that possible edge effects from the model boundary do not influence results in the area of interest. Model sensitivity testing has determined that such extents ensure proper model function without edge effects.

The STWAVE model grid was also extended seaward from the shoreline to a distance of about 3 miles. The seaward boundary is parallel to the general shoreline trend with an azimuth of 98° (Fig 3.5). This seaward boundary is defined as the y-axis of the STWAVE model, and the axis perpendicular to the y-axis pointing in the shoreline direction is denoted as the x-axis. The two axes are shown as black lines in Figure 3.5. The south and onshore boundaries are marked with red lines in the same graphic. Water depth along the seaward boundary increases from ~40 ft at the south to ~57 ft in the middle and remains 57–59 ft to the north. The grid encompasses both the project area and the identified borrow area. For all model scenarios, the grid origin is at 3057500 ft East and 586000 ft North in standard North Carolina State Plane coordinates (NAD'83), and the grid dimensions are 17,000 by 33,200 ft in the x and y directions (respectively).

3.4.2 GENESIS Model Grid

The GENESIS model domain was nested within the coverage of the STWAVE domain. The wave model domain was extended beyond the limits of the shoreline domain so that an adequate wave energy field can be generated by the wave model and passed to the shoreline model. The GENESIS model boundary is parallel to the y-axis of the STWAVE grid and is marked by a green line with an arrow pointing from north to south in Figure 3.5. The grid origin is at 3040564 ft East and 586209 ft North (NAD'83), and the grid dimension is 25,300 ft.

Ideally, the GENESIS model boundary should not only cover the project area, but should also extend some distance beyond the north and south ends of the project to eliminate any possible boundary effects and to evaluate the shoreline performance of adjacent beaches. CSE surveyed ~1 mile north and south of the project limits in October 2014, and the data provide sufficient coverage for the model application in this study.

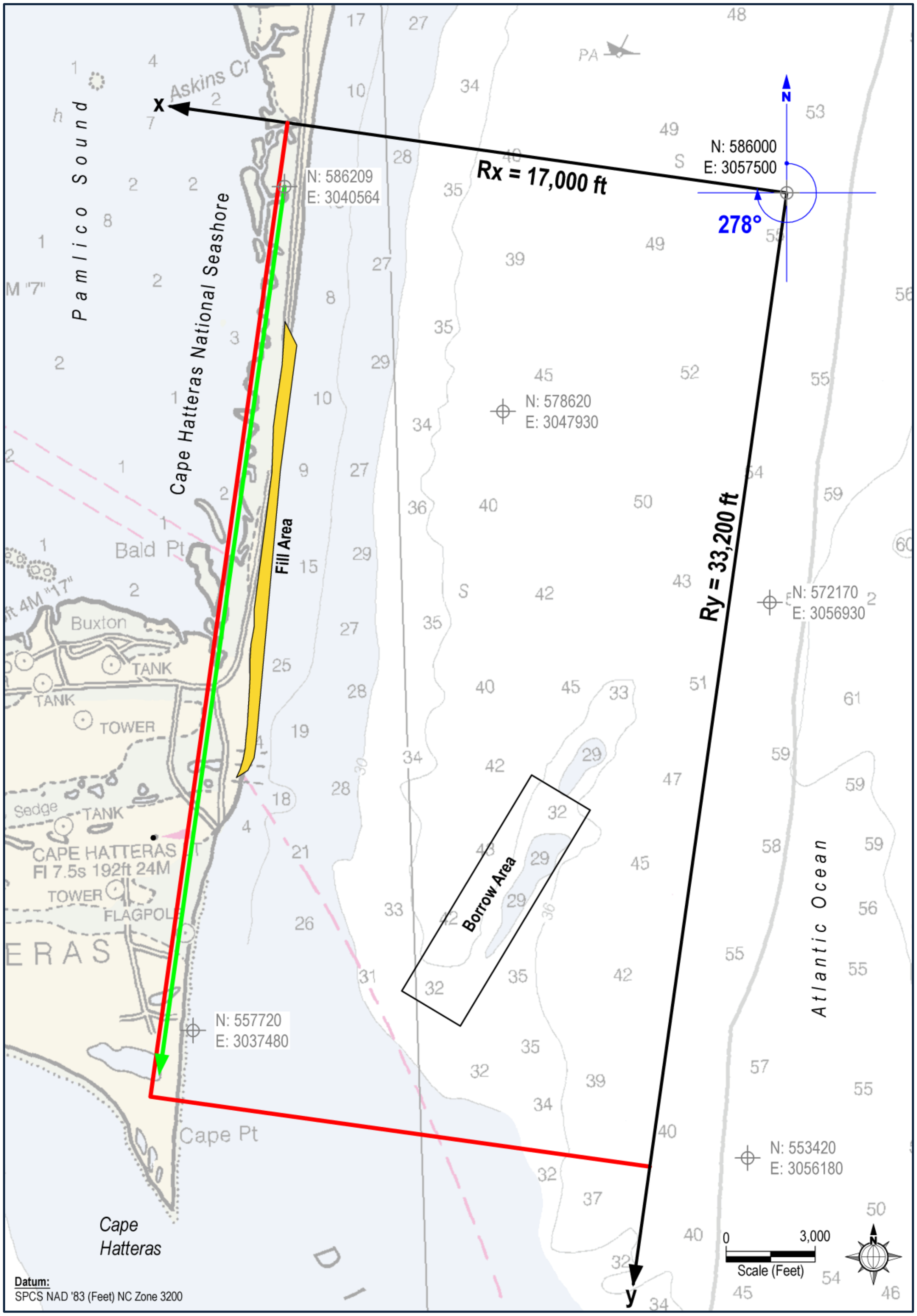


FIGURE 3.5. STWAVE and GENESIS model boundaries and grid coverage.

3.4.3 Model Grid Size

Generally speaking, if the grid cell size is smaller, then the shoreline simulation model results are more detailed. However, reducing the grid size increases the STWAVE computation time. Model sensitivity tests with different spatial resolutions ranging from 50 ft to 500 ft have been conducted, and the optimum grid size determined for this project is 100 ft for both STWAVE and GENESIS models.

3.4.4 Model Bathymetry

The setup of the STWAVE and GENESIS models requires the application of offshore and nearshore data to develop the bathymetry and topography in the model domain. Relative elevations on different vertical datum published by NOAA's National Ocean Service Tides and Currents at an adjacent site at Cape Hatteras Fishing Pier were illustrated in Figure 2.2. A detailed description of CSE's bathymetric data collection methods and data analyses is presented in Section 2, and scatter data collected in October 2014 are shown in Figure 3.6, along with model boundaries and the proposed project plan (nourishment and designated borrow area). The shoreline used in this study is defined as the 0-ft contour line relative to NAVD'88 datum.

Depth of Closure (DOC)

CSE's August 2013 and October 2014 datasets were used to determine the local depth of closure (DOC) (ie – the approximate limit of measurable bottom change over particular time scales). DOC is a critical parameter which establishes an offshore boundary for fill adjustment and erosion calculations. It is beneficial for borrow sites to be located offshore of the depth of closure location, so they will be independent of the littoral system. Borrow site locations shoreward of the closure depth position may simply shift sediment within the littoral zone and have very little impact on the net sand volume change.

Profiles from a given station were superimposed, and the difference of elevation was computed. Representative profiles are shown in Figure 3.7 with more profiles included in Attachment 5. DOC for a profile was set at the elevation at which the difference reached 0.25 ft or less. Results for the project area ranged from −19 ft to −35 ft NAVD and averaged −24 ft NAVD. Several profiles showed elevation changes below −30 ft NAVD, which may be associated with movement of small-scale sand waves (a current-generated feature in deeper water) and may not be indicative of normal onshore/offshore sediment movement in the active surf zone.

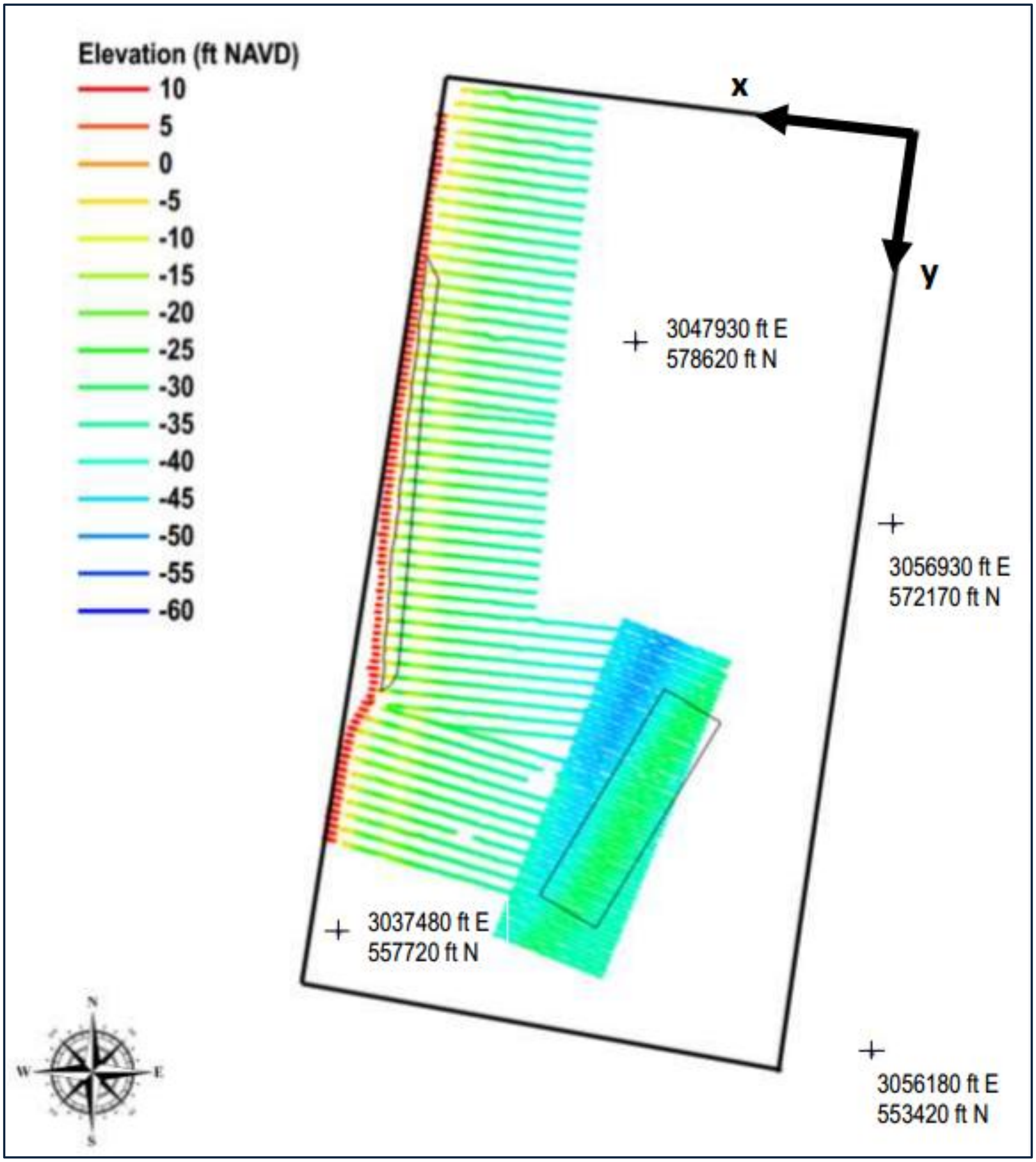
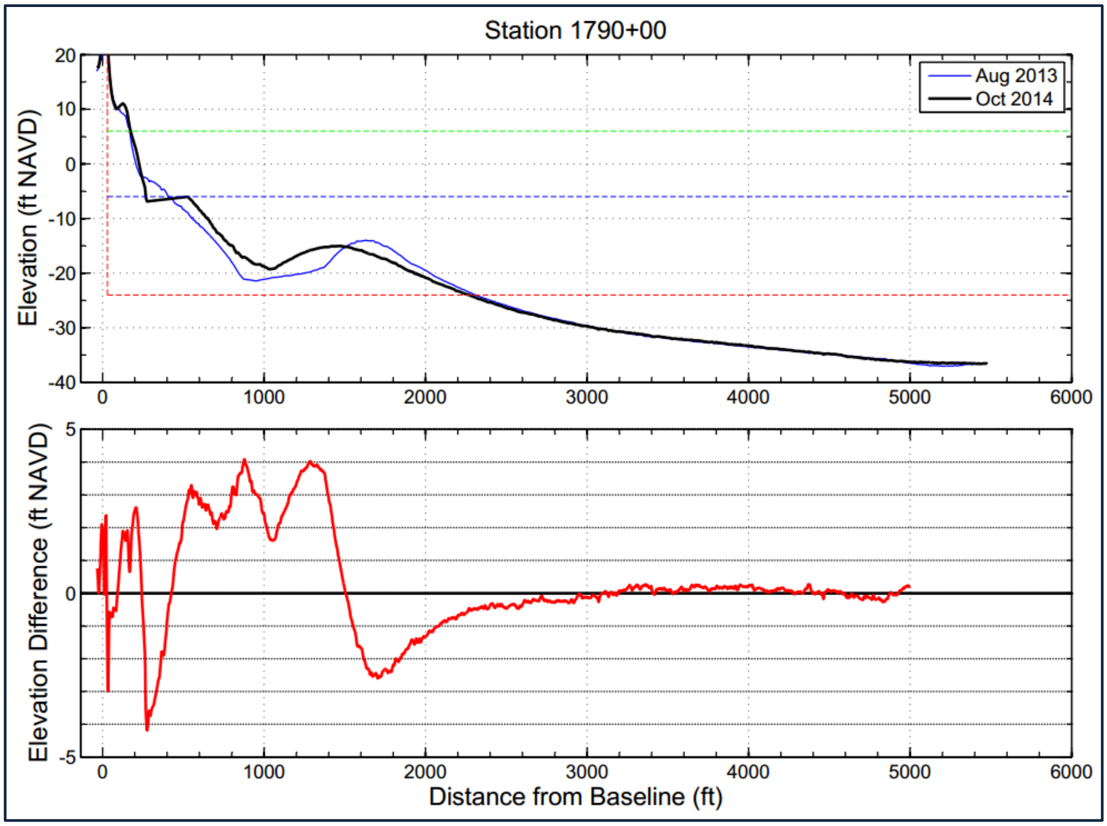


FIGURE 3.6. Bathymetric data collected by CSE in October 2014. To illustrate the relative coverage of bathymetric data to wave model computational domain, the thicker black lines in the figure represent the wave model computational domain and the thinner black lines represent the proposed beach fill and designated borrow area.



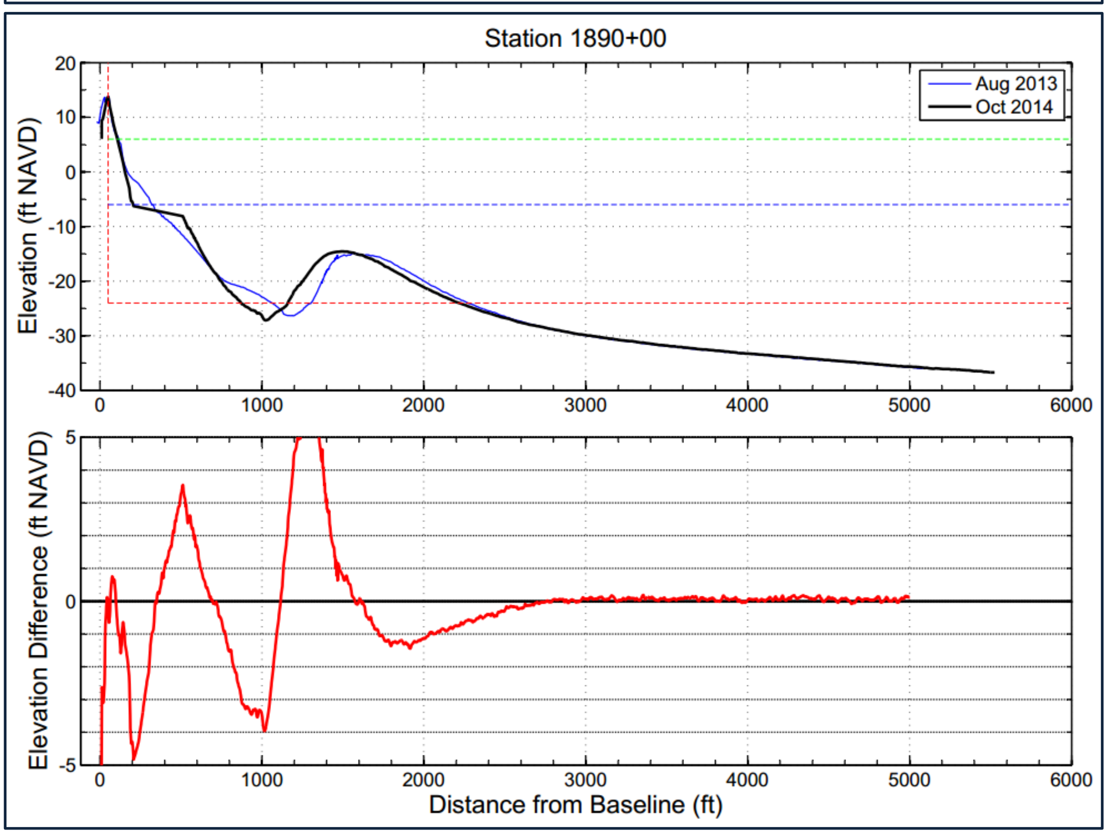


FIGURE 3.7. Profile comparison to determine the position of the depth of closure (DOC).

CSE's bathymetric survey was extended only from the shoreline seaward to a distance of ~1-2 miles. As discussed in the previous section, the model grid is extended seaward to 3 miles. Bathymetric data for the computational area between the survey limit and the grid boundary were obtained by digitizing the NOAA Navigation Chart No. 11555 (dated March 2012) for −32 ft NAVD and −62 ft NAVD contours and by extracting from the NOAA digital elevation model of Cape Hatteras (NC) (NOAA 2008).

The NOAA National Geophysical Data Center (NGDC) developed a bathymetric and topographic digital elevation model (DEM) of Cape Hatteras in July 2006 (NOAA 2008). A one-third arc-second (~10 meters or ~30 ft) elevation grid was generated from numerous, diverse digital datasets in the region. The study area covers the coastal community of Cape Hatteras, including Diamond Shoals where the designated borrow area for this project is located. The NOAA DEM 30-ft grid elevations were further simplified onto a coarser grid (150–300 ft spacing) to reduce the size of the bathymetric data file.

The data points shown in Figure 3.8 are a combination of the following bathymetric and topographic sources:

1) CSE's profile survey along the beach at 500-ft intervals in October 2014.
2) CSE's survey in the designated borrow area in October 2014.
3) NOAA navigation chart 11555 dated March 2012 (shown as nearly continuous contours of −32 ft and −62 ft NAVD).
4) NOAA DEM output elevations dated January 2008 (scattered points outside of CSE survey areas).

Figure 3.9 shows the assumed after-dredging bathymetry of the computational area (ie – the borrow area is assumed to be excavated to 7 ft below the existing grade). This is a conservative scenario for impact analysis because it represents over 5 million cubic yards of sand excavated, whereas the proposed project will only involve ~2.6 million cubic yards.

Scattered data in Figures 3.8 and 3.9 were then interpolated onto the wave model grid as shown in Figures 3.10 and 3.11. Grid dimensions of the two scenarios are the same and are specified on the figures. The "x" and "y" axes are defined as in Figure 3.8.

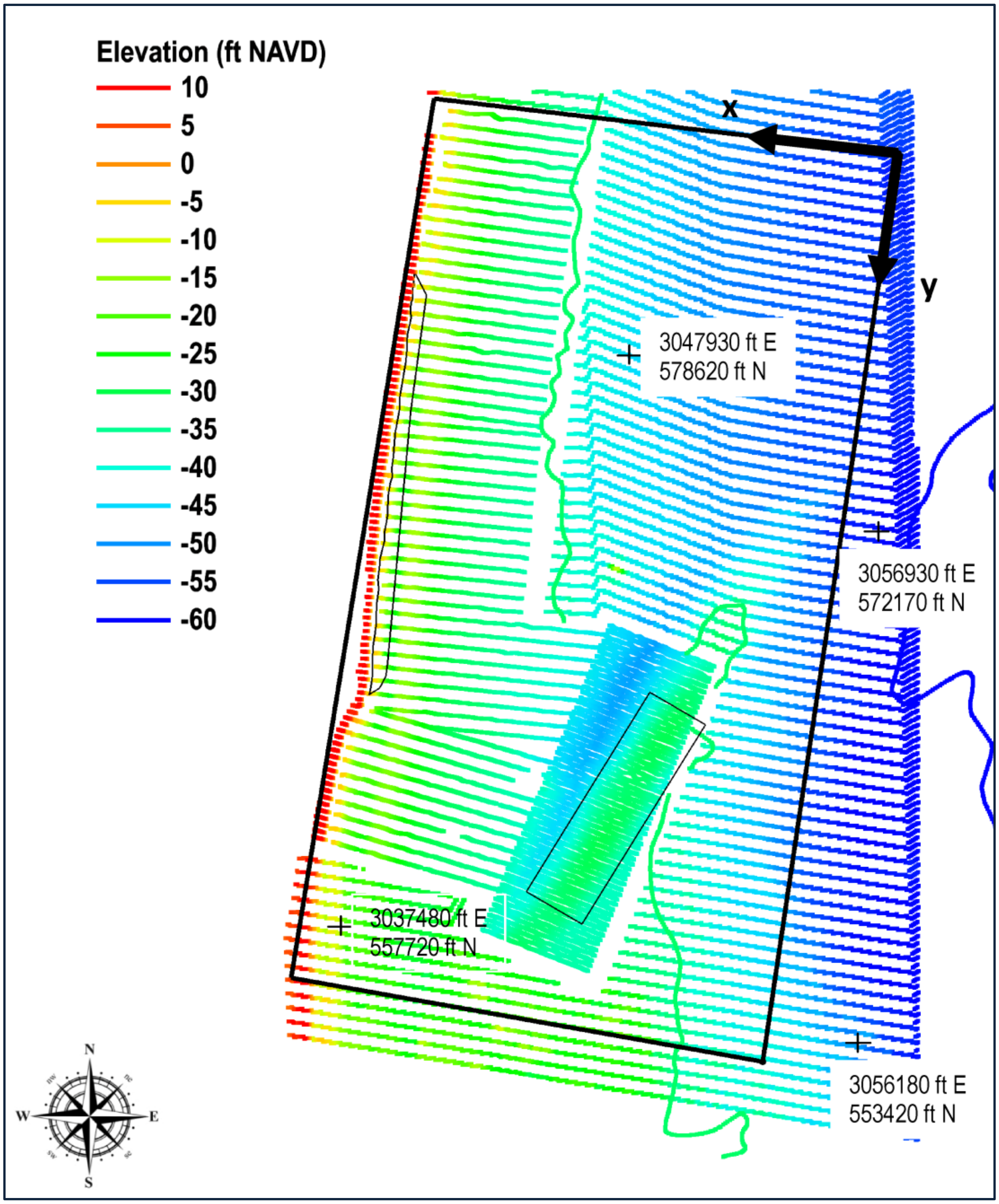


FIGURE 3.8. Combined bathymetric data used in the wave model for pre-project condition (ie – before dredging). To illustrate the relative coverage of bathymetric data to wave model computational domain, the thicker black lines in the graphic represent the wave model computational domain, and the thinner black lines represent the proposed beach fill and designated borrow area. The shoreline is on the left side of the graphic.

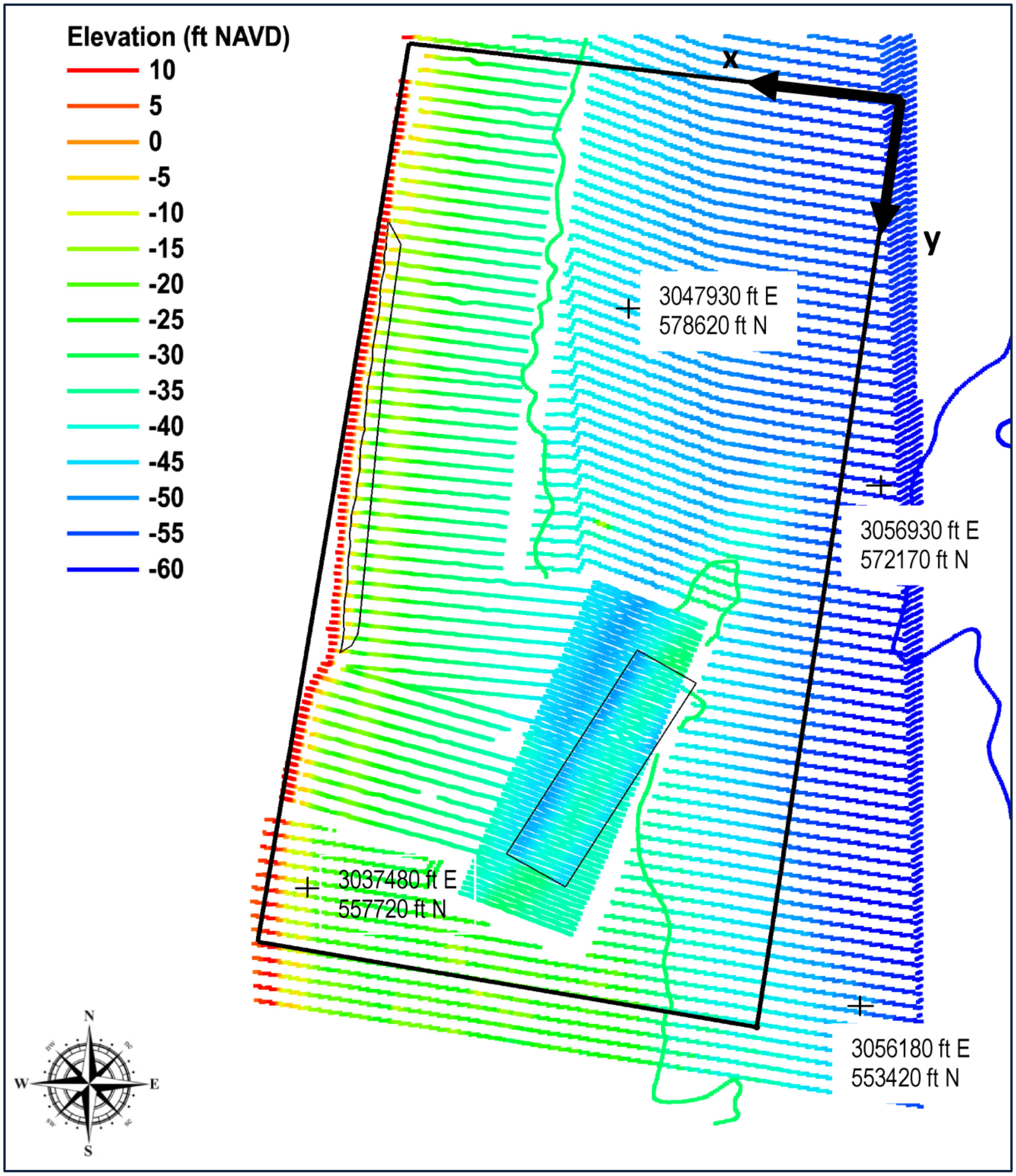


FIGURE 3.9. Combined bathymetric data used in the wave model for post-project condition (ie – after dredging). Excavation of 7 ft is assumed in the designated borrow area. It represents the biggest impact that dredging may cause to the project area. The shoreline is on the left side of the graphic.

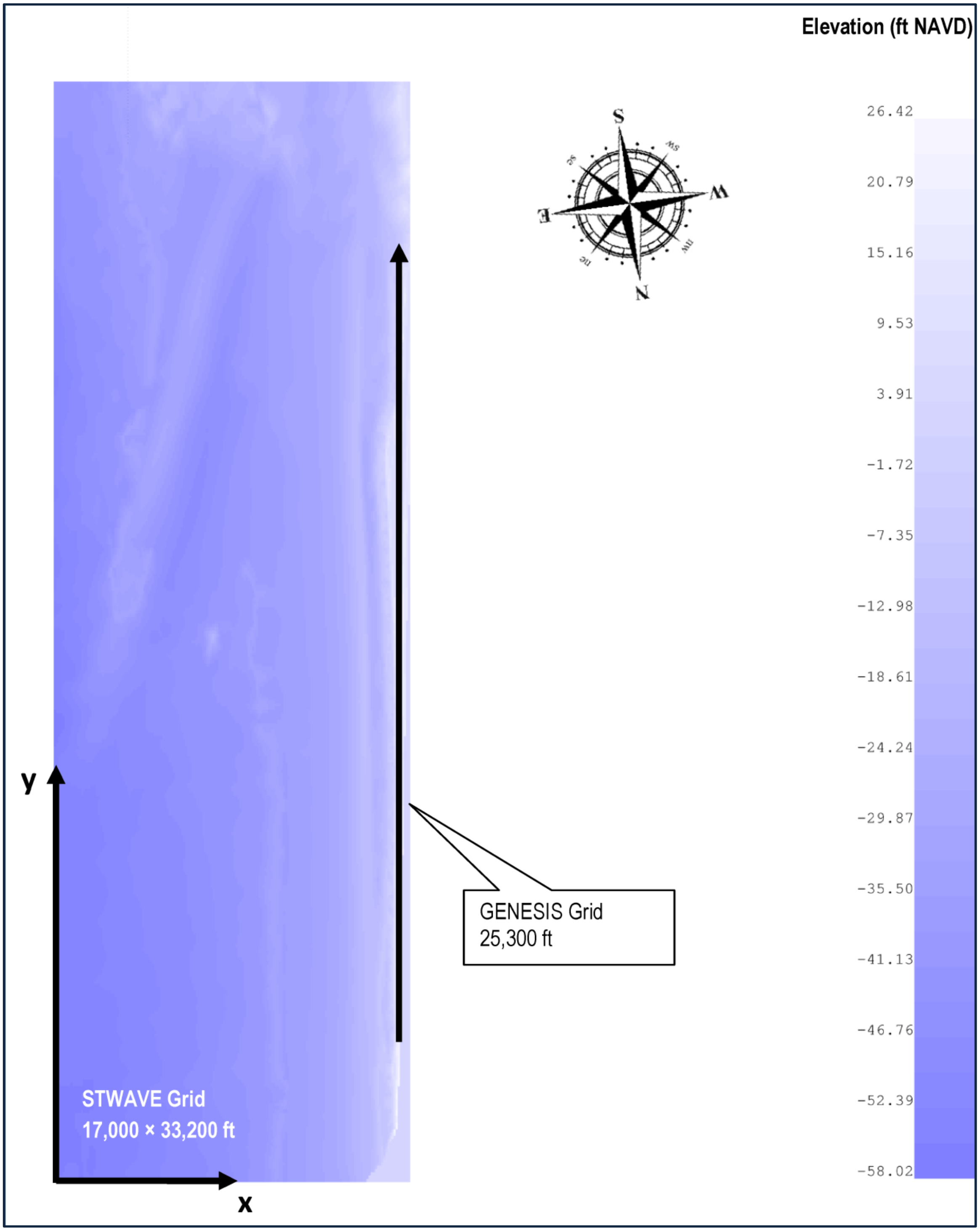


FIGURE 3.10. Model grid and interpolated bathymetry for before-dredging scenario. See Figure 3.8 for model origins and "x" and "y" axes. Notice the orientation of north indicated on the graphic. The shoreline is on the right near the GENESIS grid in this graphic.

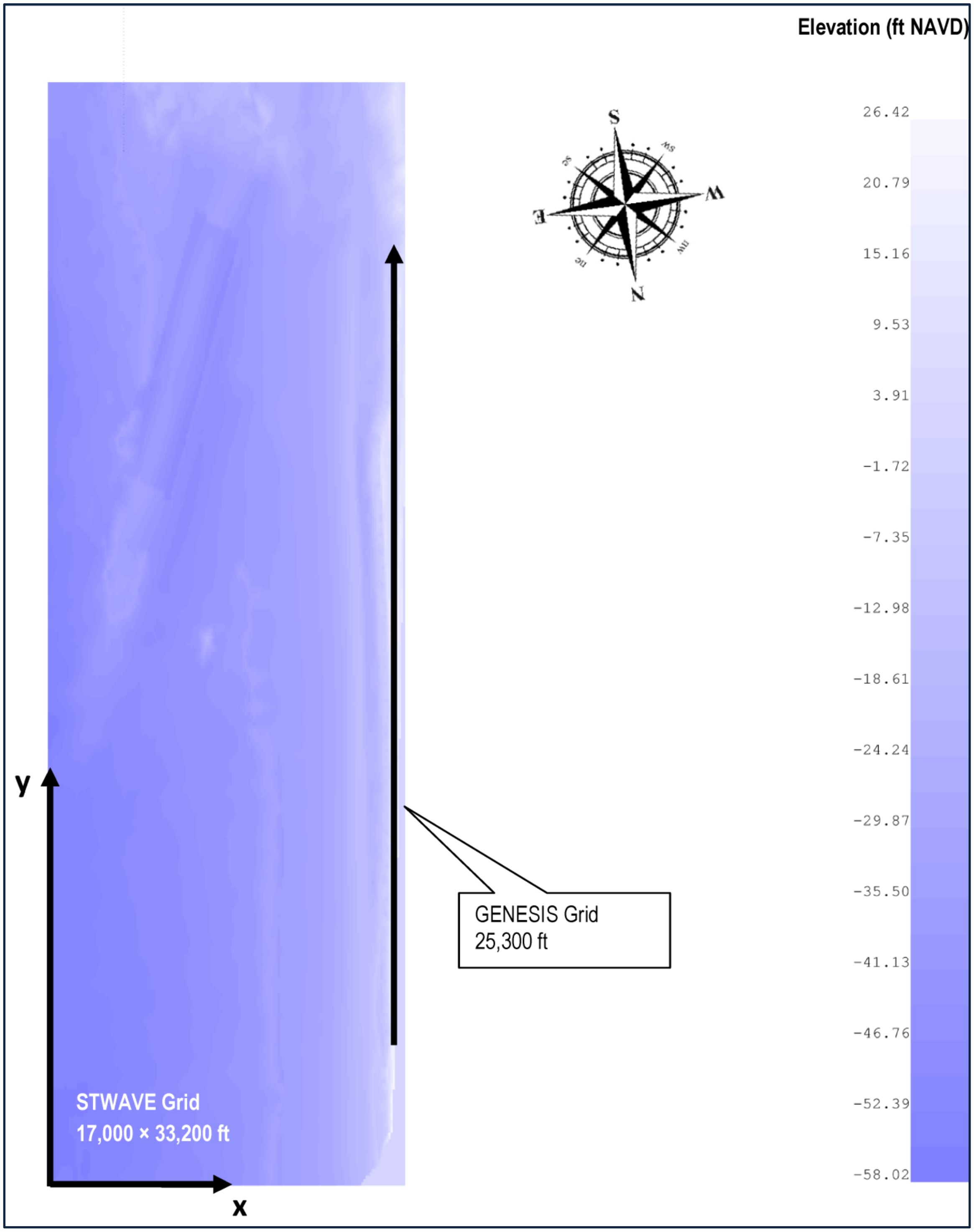


FIGURE 3.11. Model grid and interpolated bathymetry for after-dredging scenario. Model grids have the same setup as Figure 3.10.

3.4.5 Wave Climate Analysis

Obtaining satisfactory wave data is a necessary and crucial task in the preparation and execution of wave and shoreline-evolution models. There are no site-specific, long-term wave records for the Buxton project area, but there are at least two wave data sources in the vicinity of the site as discussed in the previous sections (ie – NDBC wave buoy 41025 and the WIS station 63230, see Fig 3.1 for their locations). Despite the fact that the NDBC wave buoy has real-time measurements, this station was not used because it is located ~16 miles to the southeast and it had only <3 years of wave-direction records at the time of this study.

The WIS station 63230 is located ~10.5 miles directly east of Buxton and has 33 years of hindcast data between 1980 and 2012. This station was chosen because of the long-term wave records, and the net transport generated under the wave climate of this station agreed with historical observations.

The 33-year hindcast wave climatology for WIS station 63230 cannot be directly used since the station is located over 10 miles offshore, while the wave model boundary is only 3 miles offshore. Therefore, WIS Phase III transformation technique (WISPH3) in the CEDAS software package was used first to transform time-series of wave height, period, and direction to coincide with the wave offshore boundary.

The transformed wave data was then characterized by grouping the significant wave heights, peak spectral wave periods, and vector mean wave directions at the peak spectral frequencies. The histogram and wave rose of percent occurrence of these three wave parameters are graphed in Figures 3.12 and 3.13. Bright green bins correspond to events occurring most frequently, and bright blue bins correspond to events occurring least frequently. Wave direction in these figures uses meteorological convention (ie – a wave direction of 0° corresponds to a wave that is coming from due north, and 90° is from due east). There are five wave-direction bins, four wave-period bins, and five wave-height bins categorized in this study and shown in Figure 3.12.

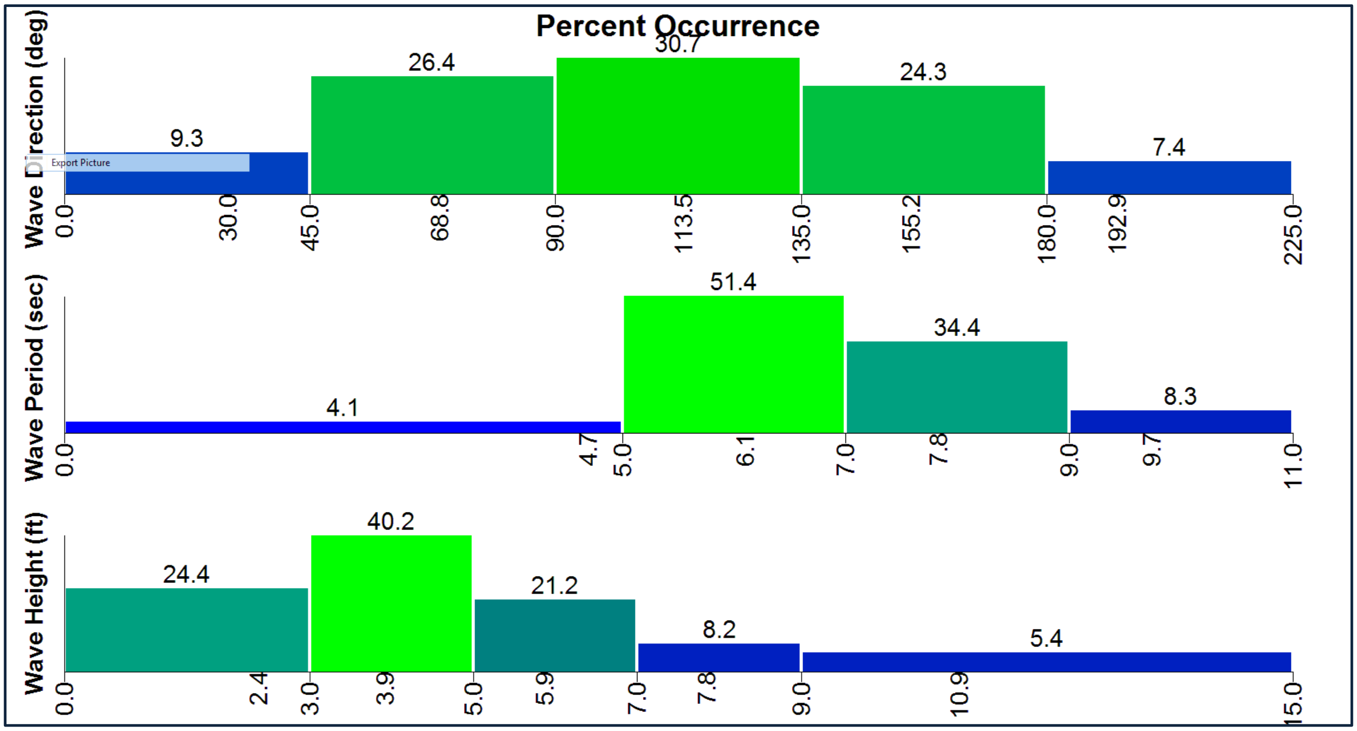


FIGURE 3.12. Histogram of percent occurrence of wave height, period, and direction for WIS station 63230.

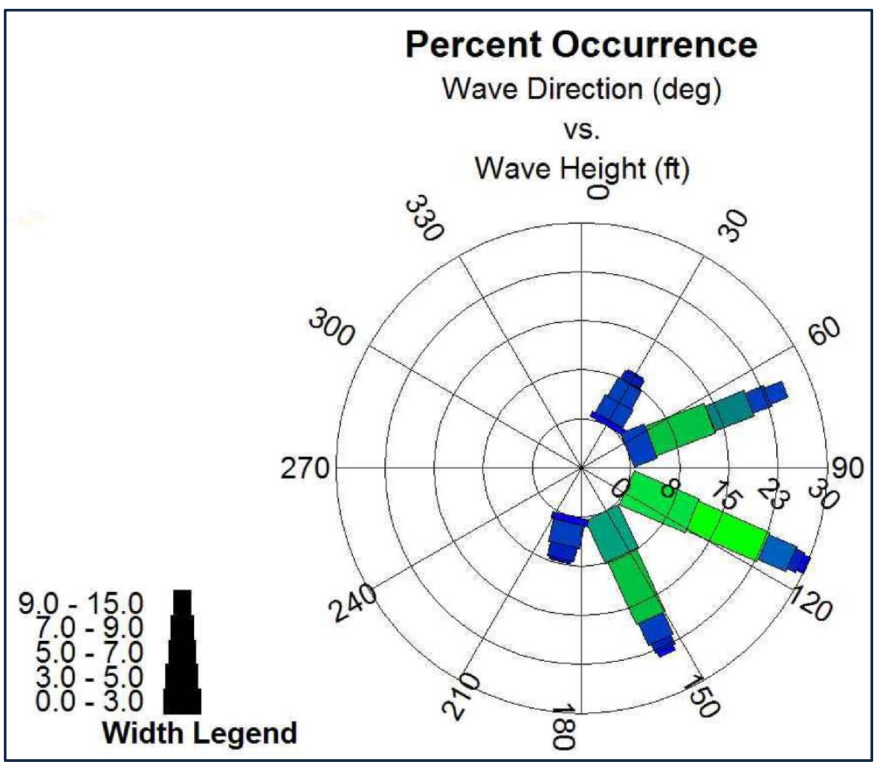


FIGURE 3.13. Wave rose of percent occurrence of wave height, period, and direction.

The largest significant wave height identified in the 33-year WIS wave hindcast was 24 ft (7.4 m). The mean significant wave height was 4.7 ft (1.44 m), and the mean wave period for this dataset was 8.6 seconds. Based on the statistical wave summary, the majority of deep-water waves approached the Buxton shoreline from easterly directions. The most predominant wave height fell within the 3–5 ft and 0–3 ft bands, and nearly 35 percent of waves exceed 5 ft. The 5–7 second wave-period band was the most dominant, containing 51.4 percent of all occurrences.

A group of 79 representative wave events was selected from all possible combinations of wave angle, period, and height bins, and was used in the STWAVE model as the input wave parameters.

3.4.6 Model Parameters

The parameters used in the GENESIS model include sand and beach data, and longshore sand transport calibration coefficients. The sand and beach data are determined from the analysis in the geotechnical study (CSE 2015) and are listed below:

Effective grain size = 0.438 mm
Average berm height = 7 ft NAVD
Closure depth = -24 ft NAVD

Volumetric erosion studies at the project area show that average annual erosion rates are estimated to be between ~114,500 cy/yr and ~129,000 cy/yr depending on the shoreline segments that were studied. The transport parameters, K_1 and K_2 required in the model were adjusted within the recommended range to obtain the best fit of simulated volumetric transport rate with historical data.

3.5 STWAVE Model Results

The borrow area for this project has an average depth of ~35 ft NAVD and a total area of 450 acres. It is located considerably outside the depth limits of significant sediment motion of the active surf zone. Sediment removal from the borrow sites will result in offshore depressions possibly 7 ft below the present bottom. To determine if the total removal of the sediment from the borrow sites would have any impact on the concentration of longshore wave energy and littoral sediment transport potential, wave transformation over the borrow sites was simulated by STWAVE by comparing conditions before and after dredging.

The STWAVE model results for one of the wave events (Event 47: H = 1.79 m or 5.87 ft, T = 5.88 seconds, Theta = 57.96°) are shown as an example in Figure 3.14 for the before-dredging scenario and Figure 3.15 for the after-dredging scenario. *[Theta or D in the graphic represents incoming wave direction to true north.]* This event represents one of the most frequent events among the 79 combinations of wave height, period, and direction. Model simulations show that other events have similar results.

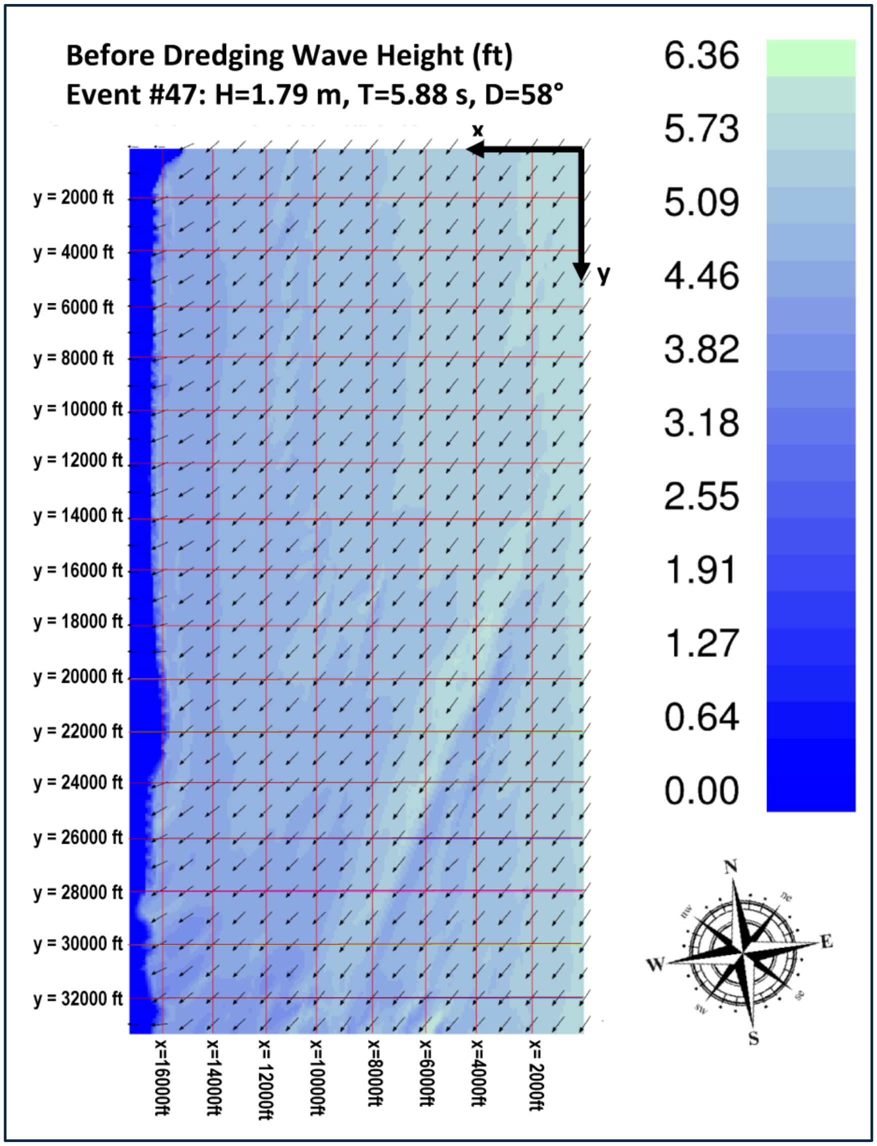


FIGURE 3.14. STWAVE simulated wave heights and directions for **before**-dredging scenario. The vertical lines represent the cross-sections in y direction that are analyzed in Figure 3.17. Lines right to left have x values of 2000 ft, 4000 ft, 6000 ft, 8000 ft, 10000 ft, 12000 ft, 14000 ft, and 16000 ft from the origin of the model. The horizontal lines represent the cross-sections in x direction that are analyzed in Figure 3.16. Lines up to down have y values of 2,000 ft, 4,000 ft, 6,000 ft, 8,000 ft, 10,000 ft, 12,000 ft, 14,000 ft, 16,000 ft, 18,000 ft, 20,000 ft, 22,000 ft, 24,000 ft, 26,000 ft, 28,000 ft, 30,000 ft, and 32,000 ft from the origin of the model. Note the orientation of north in the graphic.

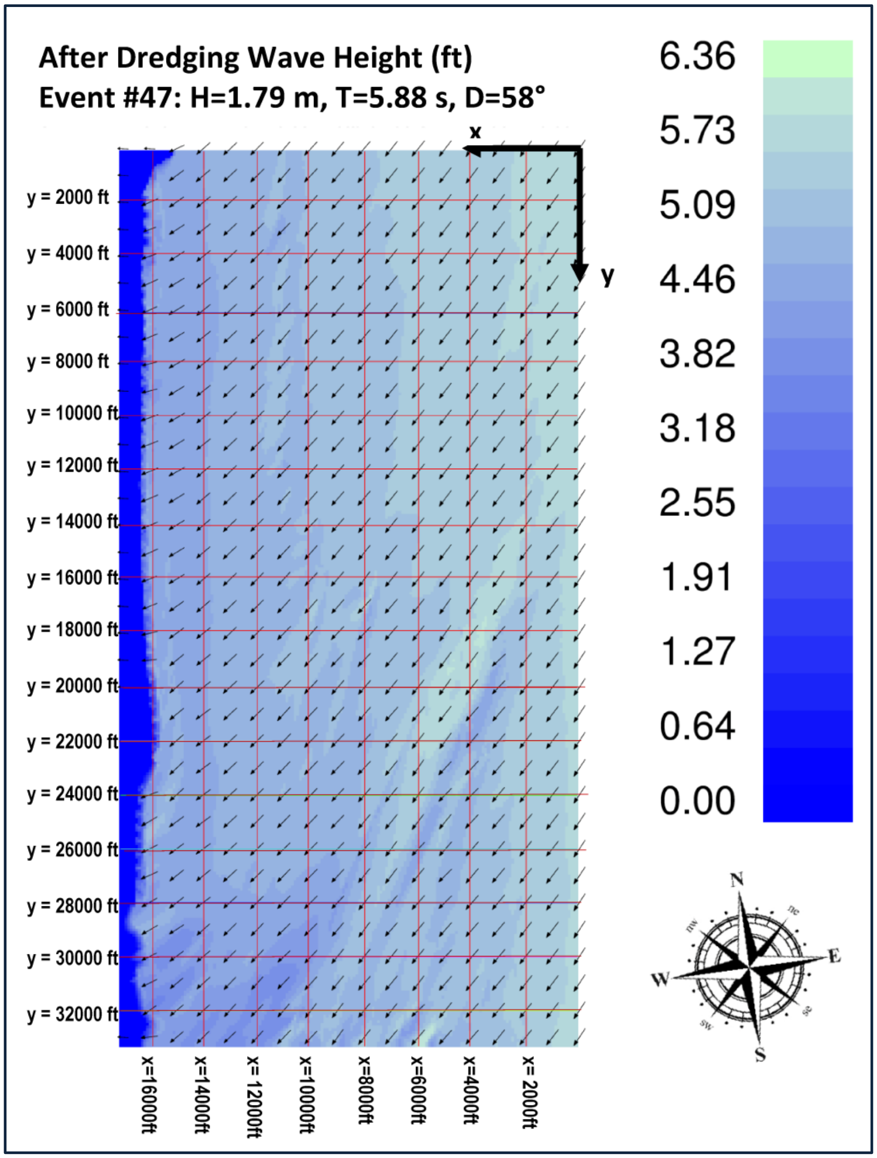


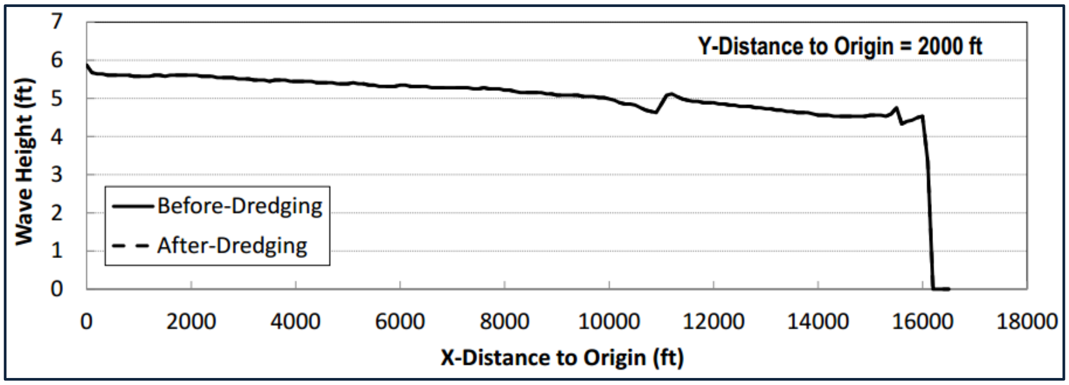
FIGURE 3.15. STWAVE simulated wave heights and directions for **after**-dredging scenario. Note the orientation of north in the graphic.

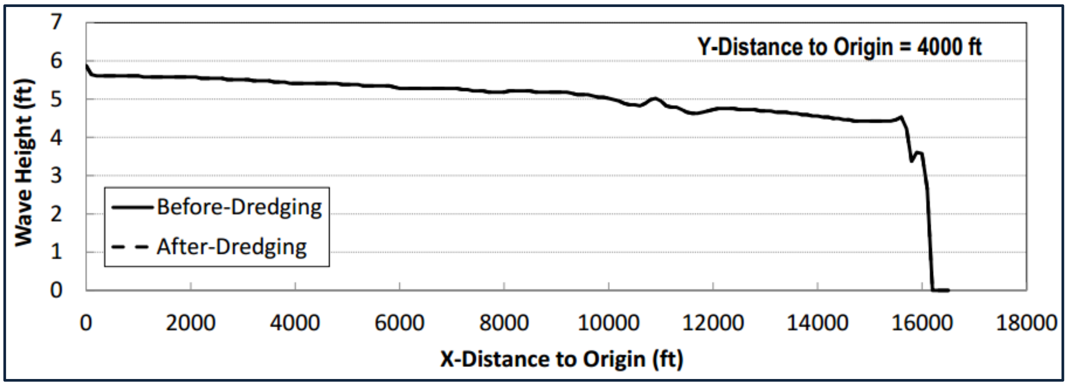
To evaluate wave pattern changes before and after dredging, 16 horizontal and 8 vertical cross-sections were chosen over the computational domain as illustrated in Figure 3.14. These cross-sections effectively cover the study area including the designated borrow area. Wave heights across horizontal cross-sections are plotted in a series of graphics in Figure 3.16 (4 pgs), and wave heights across vertical cross-sections are plotted in a series of graphics in Figure 3.17 (2 pgs). Some key coordinates, dimensions, and relative distance to the model origins are listed below.

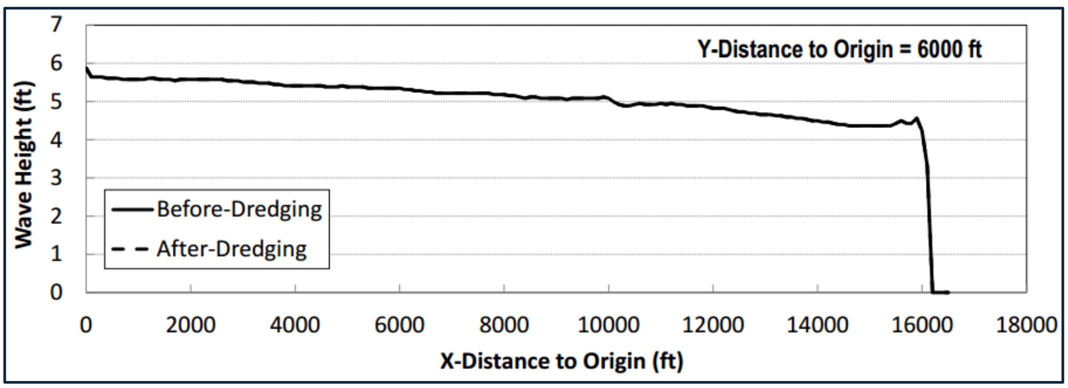
STWAVE Model Origin:	x_0 = 3057500 ft, y_0 = 586000 ft
STWAVE Grid Length in "x" Direction equals:	17,000 ft
STWAVE Grid Length in "y" Direction equals:	33,200 ft
Project Northernmost Limit to STWAVE Origin:	y = ~6,400 ft
Project Southernmost Limit to STWAVE Origin:	y = ~21,900 ft
Borrow Area to Model Origin:	20,700–29,000 ft in "y" direction and 3,500–9,000 ft in "x" direction

In Figure 3.16, the left side of the x-axis represents offshore, and the right side of the x-axis represents onshore. The first ten plots in this graphic show no difference in wave height before and after dredging, and the eleventh plot (ie – y-distance to origin = 22,000 ft) shows minor differences in wave height between these two scenarios. Since the project area is above "y" = 21,900 ft, the results indicate that borrow-area dredging has no impact or negligible impact to the wave field in the project area and directly offshore of the project area. Starting from the twelfth plot (ie – y-distance to origin = 24,000 ft) differences in wave height between the two scenarios became more noticeable, but the greatest difference occurs within an area between "x" = 4,000 ft and 9,000 ft where the borrow area is located.

The last plot in Figure 3.16 (ie – y-distance to origin = 32,000 ft) shows the biggest impact area extended to x-distance of 14,000 ft (or ~3,000 ft from the shoreline), but the wave height difference diminishes toward the shore. The largest wave height increase after dredging was ~0.5 ft (~10 percent of the local wave) and occurred near the center of the south borrow area where x = ~6,000–7,000 ft and y = 28,000–30,000 ft. In Figure 3.17, x-axis represents y-distance to the model origin, and the further left means further north. All plots in this graphic show no difference in wave height before and after dredging except for the area of the borrow area (ie – x is approximately between 3,500 and 9,000 ft and y is approximately between 20,700 and 29,000 ft). The increase in the wave height over the borrow area is similar in magnitude to the results shown in Figure 3.16.







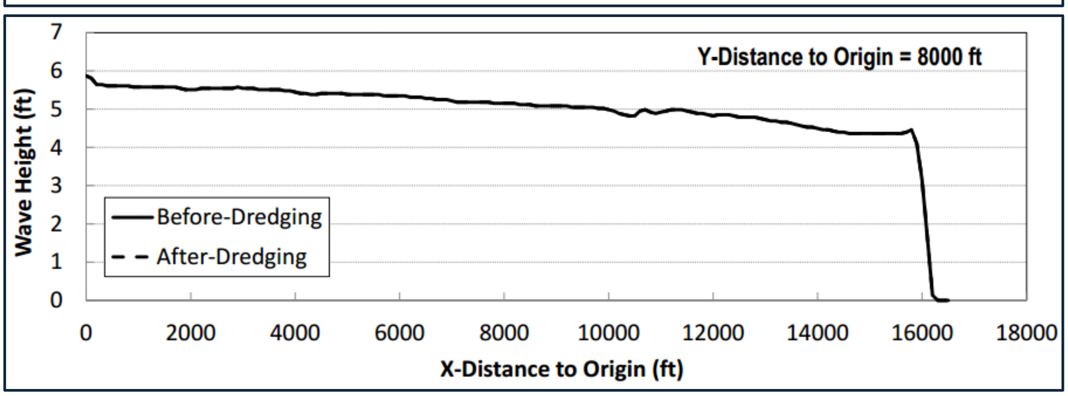


FIGURE 3.16(1-4). STWAVE simulated wave height comparisons at different horizontal cross-sections parallel to the "x" axis (ie – with constant distance to the origin in the "y" direction) as illustrated in Figure 3.14. "0" is the offshore model boundary and the shoreline is at the right side of the graph.

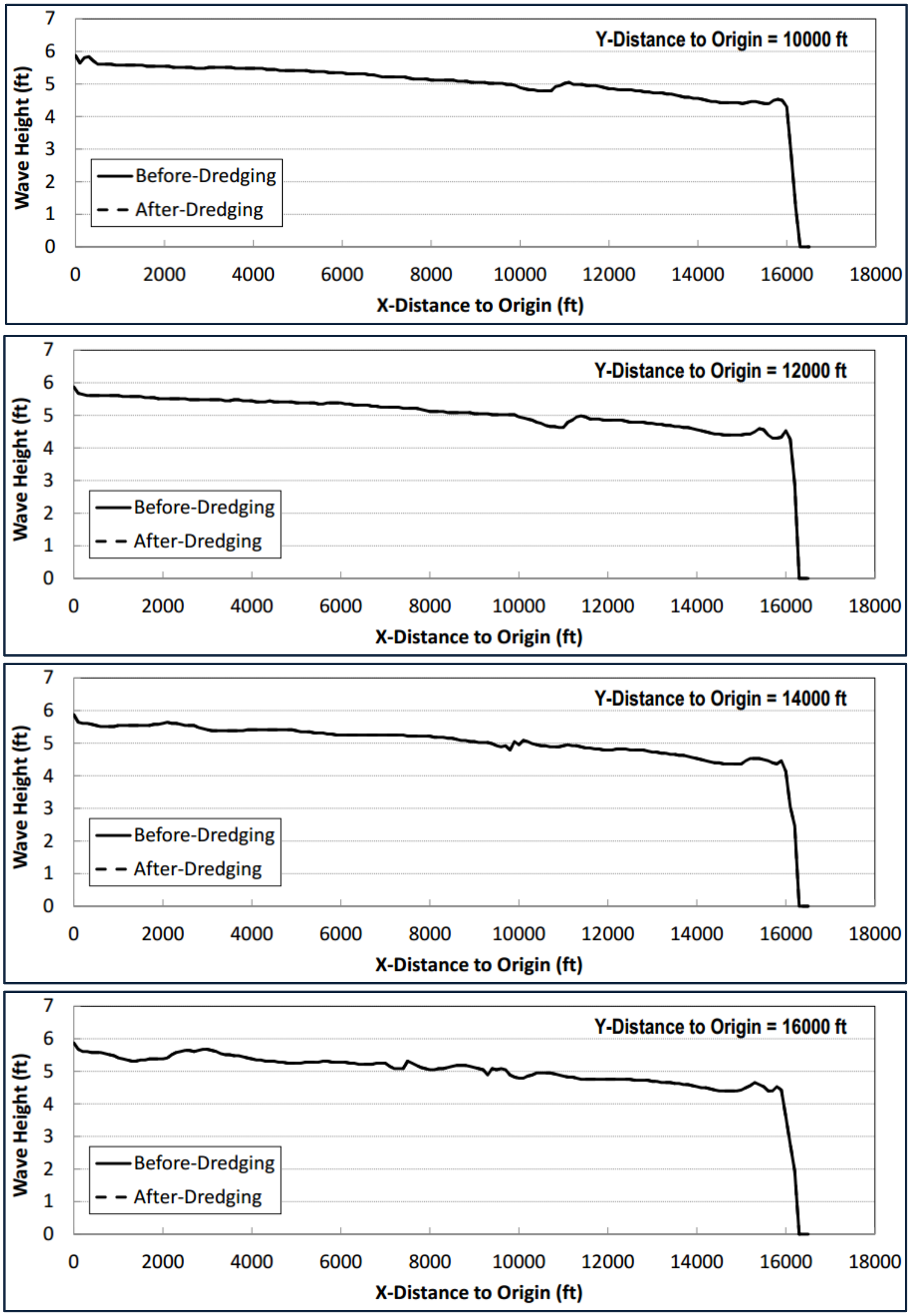


FIGURE 3.16(5-8). STWAVE simulated wave height comparisons at different horizontal cross-sections parallel to the "x" axis (ie – with constant distance to the origin in the "y" direction) as illustrated in Figure 3.14. "0" is the offshore model boundary and the shoreline is at the right side of the graph.

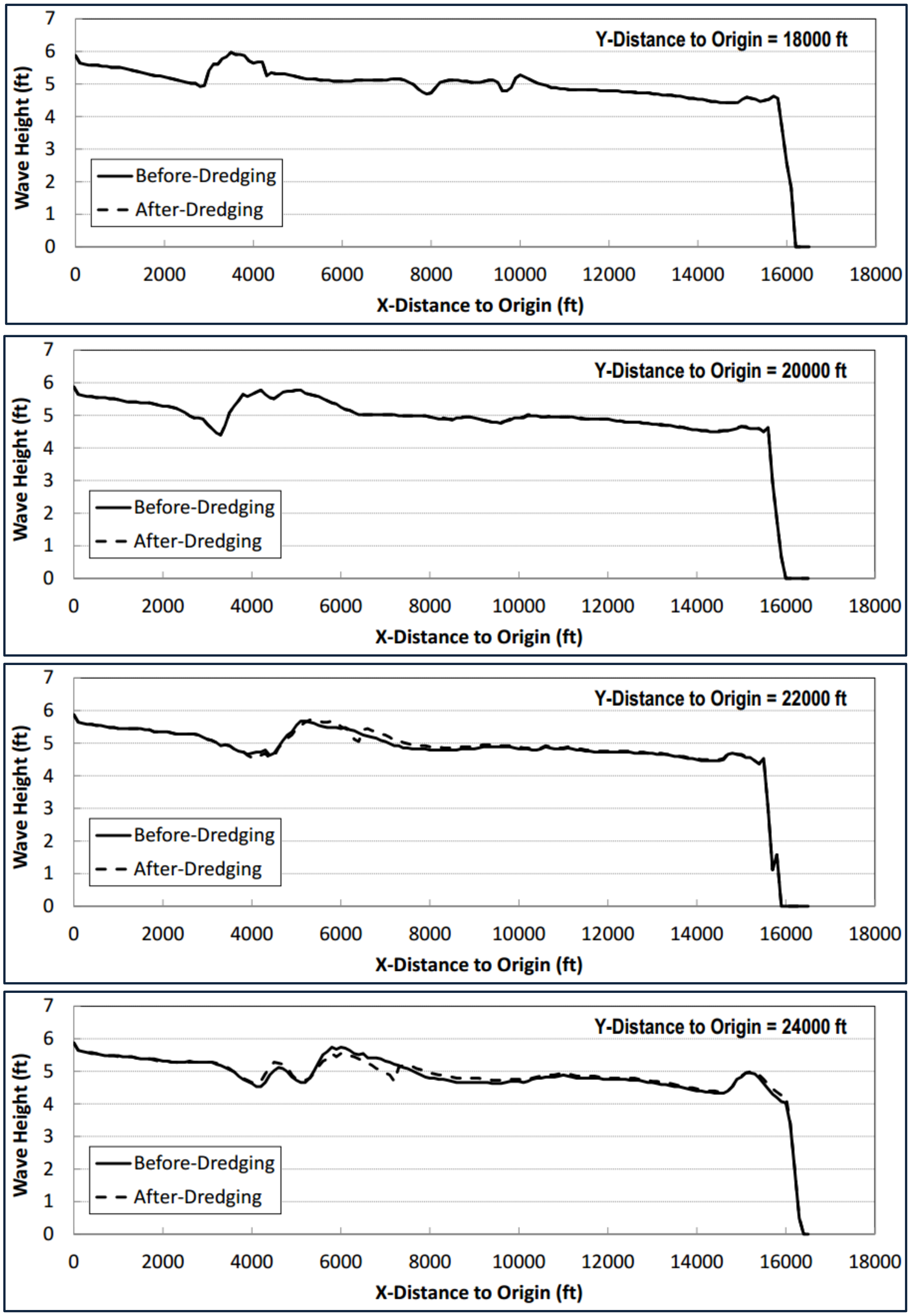


FIGURE 3.16(9-12). STWAVE simulated wave height comparisons at different horizontal cross-sections parallel to the "x" axis (ie – with constant distance to the origin in the "y" direction) as illustrated in Figure 3.14. "0" is the offshore model boundary and the shoreline is at the right side of the graph.

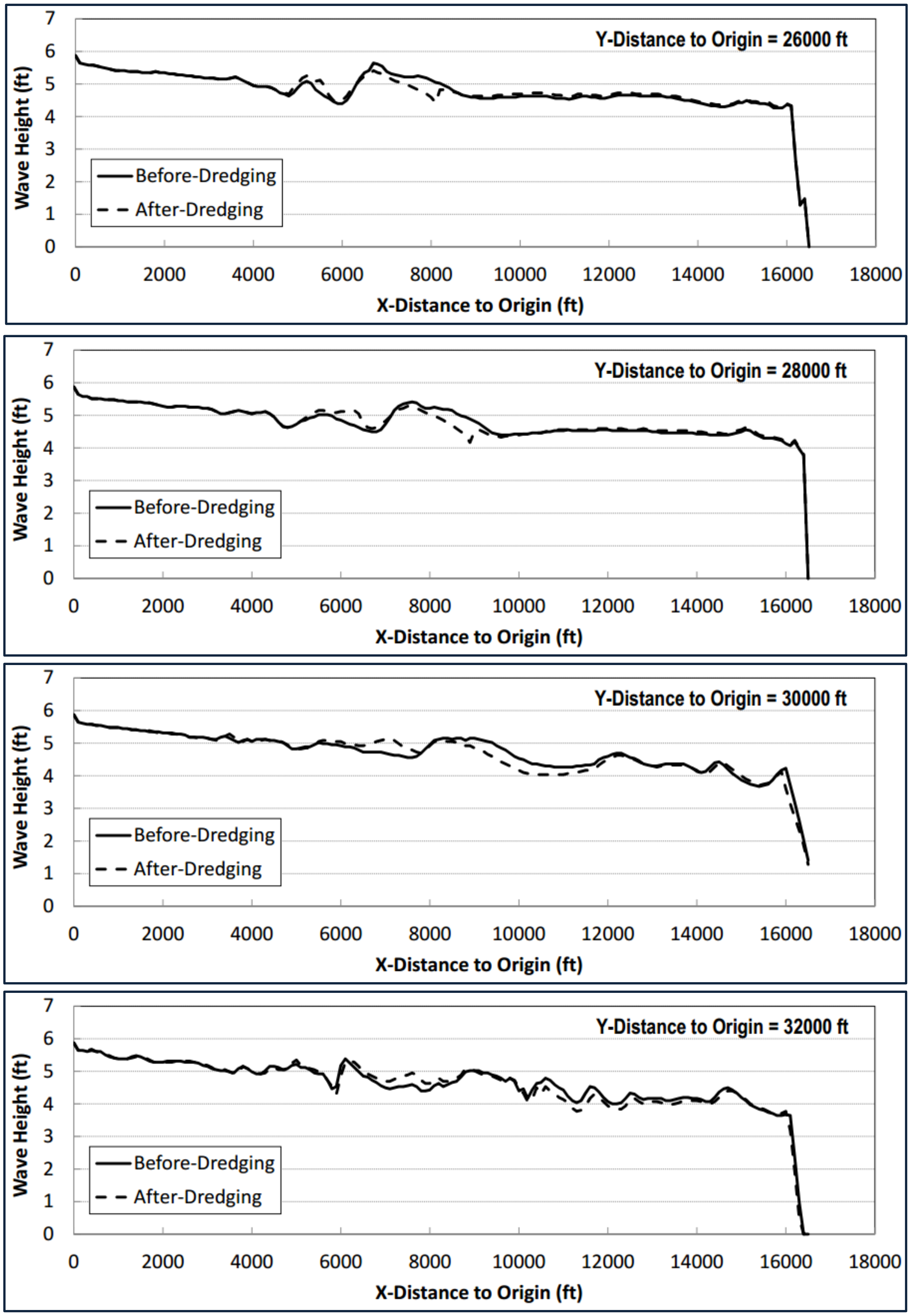


FIGURE 3.16(13-16). STWAVE simulated wave height comparisons at different horizontal cross-sections parallel to the "x" axis (ie – with constant distance to the origin in the "y" direction) as illustrated in Figure 3.14. "0" is the offshore model boundary and the shoreline is at the right side of the graph.

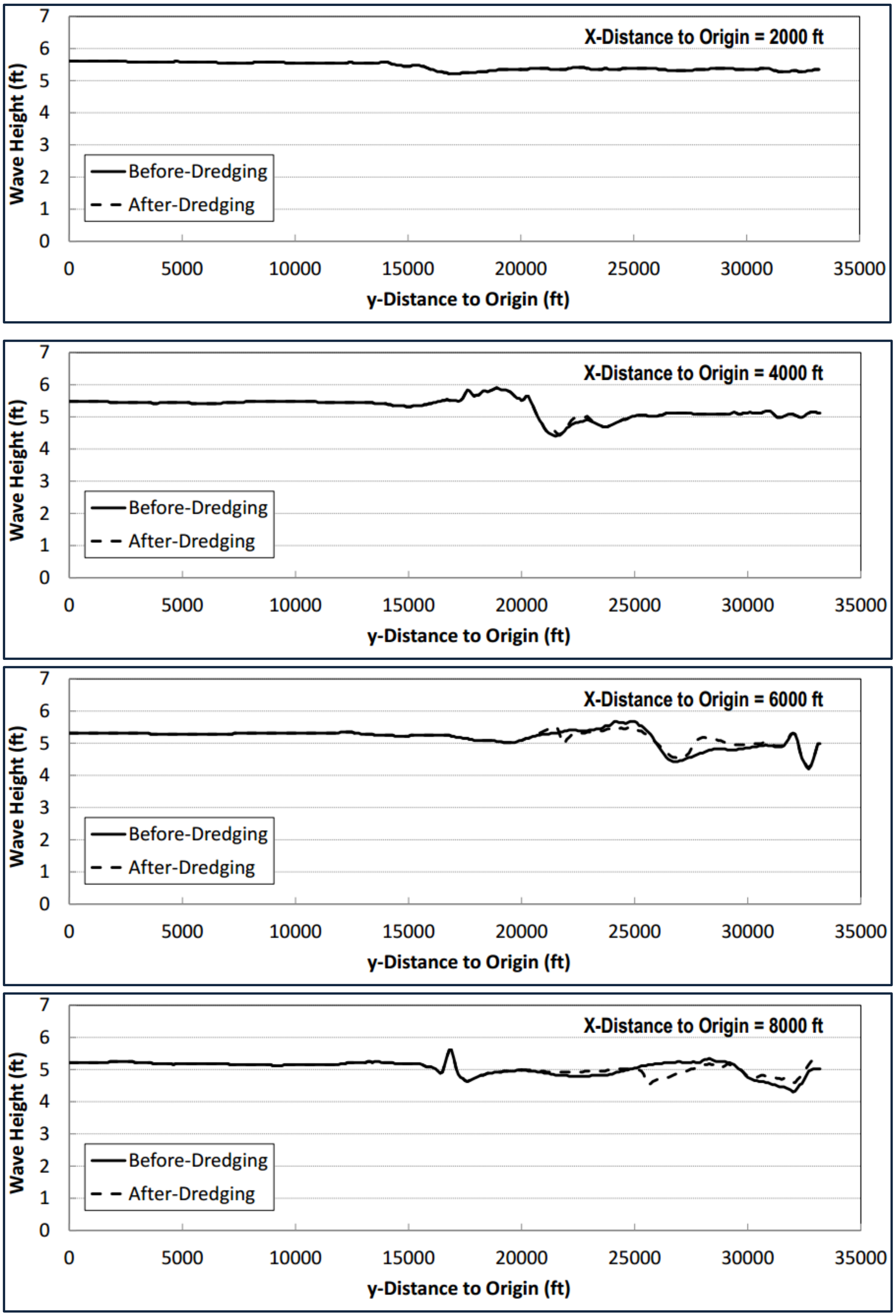


FIGURE 3.17(1-4). STWAVE simulated wave height comparisons at different vertical cross-sections parallel to the "y" axis (ie – with constant distance to the origin in the "x" direction) as illustrated in Figure 3.14.

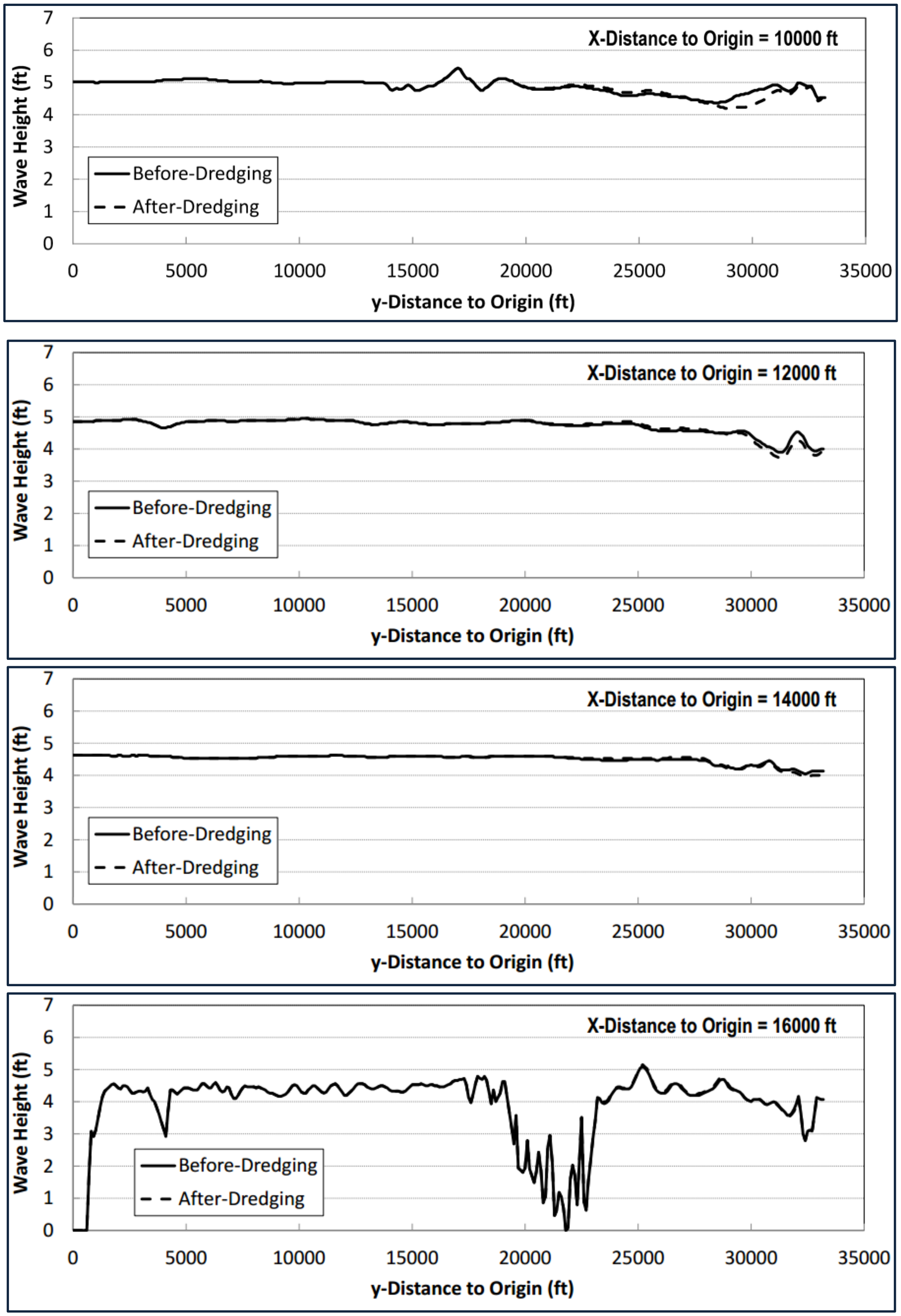


FIGURE 3.17(5-8). STWAVE simulated wave height comparisons at different vertical cross-sections parallel to the "y" axis (ie – with constant distance to the origin in the "x" direction) as illustrated in Figure 3.14.

In conclusion, the STWAVE model results indicate that borrow-area dredging will not impact the wave patterns along the project beach; the impact will be concentrated in the dredged area and its immediately adjacent area. The biggest wave height increase will be ~10 percent of the local wave (expected to occur in the center of the south borrow area) under this event. Similar results for an event where waves originate from southeast are included in Attachment 6. Other events are anticipated to produce similar, but lesser, impacts than the two wave directions noted in Figures 3.14–3.15 and Attachment 6.

The pre-project depth in the borrow area is 10–30 ft deeper than the estimated DOC of this area, and the results show that the proposed maximum excavation of 7 ft will not significantly modify the wave patterns at the shore and will only locally modify waves within the immediate borrow area. The results also show that the location of the borrow area will not significantly modify sand transport processes and rates over the excavation area, and will not impede or modify normal onshore sand transport.

3.6 GENESIS Model Calibration

Proper application of GENESIS requires the model to be calibrated by adjusting the various model parameters until it can reasonably reproduce historical shoreline change or longshore sediment transport rates over a given time interval. Because the Buxton area does not have more than two sets of complete shoreline data for the calibration procedure, the net longshore sediment transport rates and total volumetric erosion rates simulated were used to compare with historical erosion rates.

Figure 3.18 shows calculated, average annual net longshore sediment transport rates along the modeled shoreline over a specific 10-year period between 1980 and 1989 as an example. Moving from left to right along the horizontal axis represents the shoreline from north to south, and positive transport rates denote net sand movement to the south. Some key reference distances are listed below:

Project Northernmost Limit (sta 1770+50) to GENESIS Origin: ~5,000 ft
Project Southernmost Limit (sta 1925+50) to GENESIS Origin: ~20,500 ft

Figure 3.18 shows that the sediment transport rate varies along the shoreline, increases from north to south, and is southerly which is consistent with the historical trend of sediment movement and spit accretion in this area. Transport rates increase markedly near station 1875+00 (or a distance to the model origin of 15,500 ft), and reach the highest near the south boundary of the proposed project. The increasing transport rate explains the higher erosion observed at Buxton Village. Using the same two reaches as the previous section, the simulated average annual net transport rate for the shoreline segment between stations 1805+00 and 1920+00 (or a distance to GENESIS origin between ~8,500 ft and ~20,000 ft) was ~117,500 cy; for the shoreline segment between stations 1790+00 and 1928+00 (or a distance to GENESIS origin between ~7,000 ft and 20,800 ft), the rate was ~122,000 cy. These average annual rates are consistent with the net annual erosion rates derived from NCDENR shoreline change data (extrapolated to volumetric losses) as discussed in the previous section.

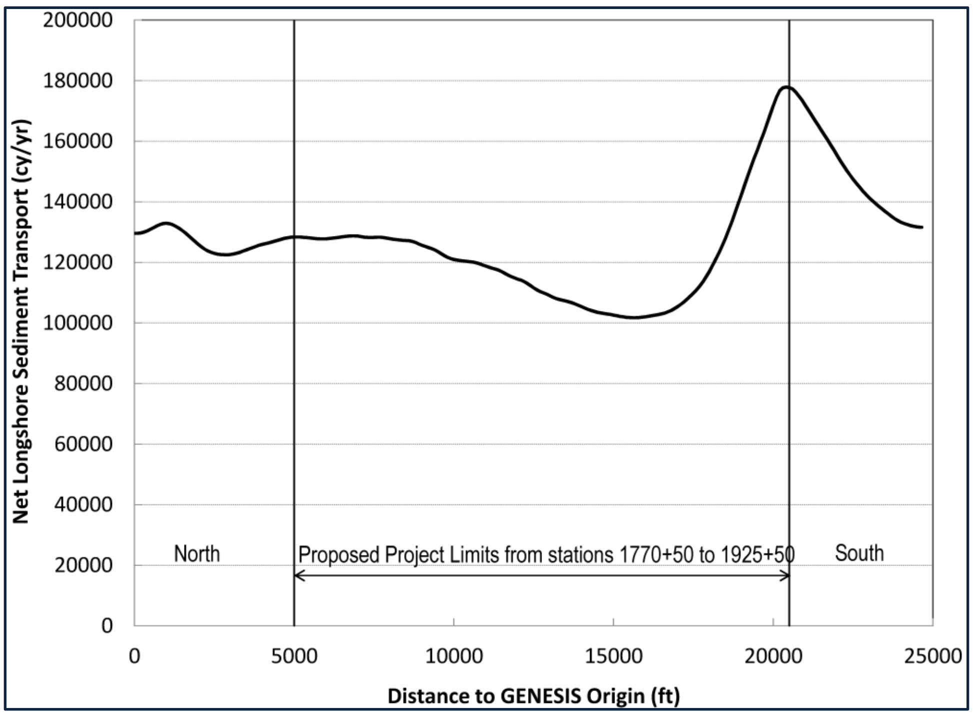


FIGURE 3.18. Average annual longshore net sediment transport rates over 10-year period for pre-project condition. Positive rates denote net sand movement to the south.

Figure 3.19 represents calculated, annual net longshore sediment transport rates along the modeled shoreline over a particular year (eg – 1985–1986). Negative rates indicate the transport direction was northerly. Previous studies show that the net transport rate is highly sensitive to wave direction (CERC 1984, Komar 1998), and the sediment transport rates along the northern Outer Banks are sometimes northerly as was the case between 2003 and 2005 at Nags Head (CSE 2011). The historic longshore transport direction is generally assumed to be southerly there. Byrnes et al (2003) also reported multi-year periods of net northerly transport north of Oregon Inlet. Therefore, it is possible that net sediment movement is to the north over certain time periods in the Buxton area. The GENESIS model successfully captures this periodic transport reversal.

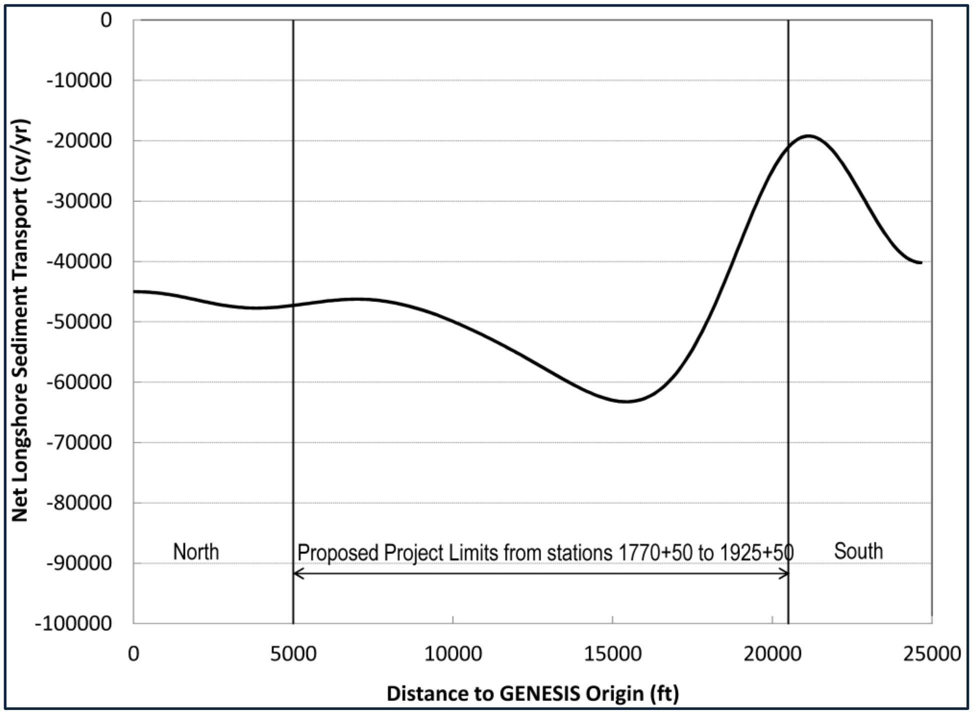


FIGURE 3.19. Annual longshore net sediment transport rates for a particular year (eg – 1985–1986) for pre-project condition. Negative rates denote net sand movement to the north.

In conclusion, the net longshore sediment transport rate predicted by the GENESIS model agrees closely with the estimated volumetric loss rates of ~114,500 cy/yr and ~129,000 cy/yr. Due to lack of historical shoreline measurements for this area, the model cannot be further calibrated for shoreline evolution. Because the model will be primarily used to evaluate the impact of the proposed nourishment and offshore borrow area dredging on sediment transport rates, such calibration is not expected to hinder the comparative results.

3.7 GENESIS Model Results

The project calls for a maximum of 2.6 million cubic yards of beach quality sand to be pumped from the designated offshore borrow area onto 15,500 linear feet of ocean beach. The designed berm height is 7 ft NAVD, and the average fill density is ~168 cy/ft. Fill densities will vary from north to south in accordance with the historical erosion rates, and the center of the project will receive the highest fill density upward of ~300 cy/ft (CSE 2013). To determine if nourishment on the beach and removal of the sediment from the borrow sites would have any impact on the longshore sediment transport potential, GENESIS was used and results were compared for pre- and post-project conditions.

Net sediment transport rates after the project are plotted in Figure 3.20 along with the rates before the project, and the differences between these two scenarios are plotted in the same graphic. The average annual net transport rate after the project for the shoreline segment between stations 1805+00 and 1920+00 (or a distance to GENESIS origin between ~8,500 ft and ~20,000 ft) was ~117,700 cy; for the shoreline segment between stations 1790+00 and 1928+00 (or a distance to GENESIS origin between ~7,000 ft and 20,800 ft), the rate was ~122,500 cy. These rates are almost identical to the rates before the project. It indicates that nourishment and borrow area dredging will cause negligible changes in the net long-shore sediment transport rate. The rates will change locally as shown in Figure 3.20 where beach fill is conducted, but there will be no changes ~0.5 mile north or south of the project area.

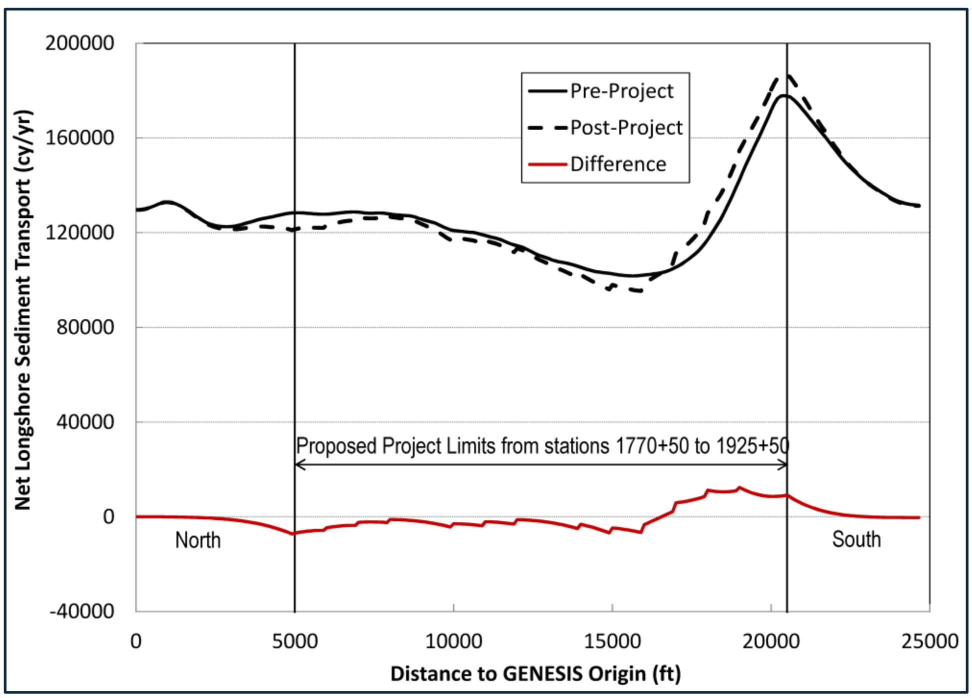


FIGURE 3.20. Comparison of annual net longshore sediment transport rates before and after the nourishment project.

3.8 Conclusions

STWAVE and GENESIS have been widely applied in coastal engineering and planning projects for predicting the behavior of wave field and longshore transport. They were used in this study to simulate wave patterns and longshore sediment transport rates before and after the proposed nourishment project. Results were used to evaluate the impact of borrow area dredging and beach fill on wave height and longshore transport rates along the study area, which includes a section of the Cape Hatteras National Seashore adjacent to the Village of Buxton.

The STWAVE model results indicate that borrow area dredging will not cause any measurable wave pattern changes in the project area, and the impact will be concentrated within the dredged area and its immediately adjacent ocean bottom. The biggest wave height increase will be no greater than 10 percent of the local wave and is expected to occur in the borrow area. The pre-project depth in the borrow area is 10–30 ft deeper than the estimated DOC in this setting, and therefore well beyond any expected zone of normal exchange of sediment with the beach. The STWAVE model results show that the proposed excavations up to 7 ft will have only a minor local impact on waves in the immediate borrow area and negligible impact on waves at the beach. The results also show that sand transport will not be significantly modified over the borrow area and that normal onshore sand transport will continue uninterrupted.

The GENESIS model was first calibrated using estimated erosion rates of 114,500 cy/yr to 129,000 cy/yr. The calibrated model results yielded 117,500 cy/yr to 122,000 cy/yr annual, net sediment transport rates, which are in close agreement with the estimated rates. The calibration results show that the model is able to capture the overall sediment transport pattern and can be used to evaluate the relative changes of sediment transport rates before and after nourishment and offshore borrow-area dredging.

The model simulation for potential after-project longshore transport along two segments of shoreline resulted in only minor changes compared to the before-project condition (of the order of hundreds of cubic yards). The model results indicate that nourishment and borrow area dredging will cause negligible changes in the longshore sediment transport rate. The rate will change locally where beach fill is conducted, but there will be no changes ~0.5 mile north or south of the fill area.

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ATTACHMENT 1

A) Baseline Control Points & Stationing

CSE Profile Stations & Azimuths

B) August 2013 Surveys

C) October 2014 Surveys

ATTACHMENT 1A. Project baseline (BL) and stationing for Hatteras Island (NC) between Oregon Inlet and Cape Point referenced in the present report.

CSE Dare County Baseline Table						
Coordinate System: *US State Plane 1983* ***Zone:*** *NC 3200*						
Horizontal Datum: *NAD 1983 (feet)* ***Vertical Datum:*** *NAVD 1988 (feet)*						
Station	***Northing***	***Easting***	***Elevation***	***Monument***	***Locality***	***Note***
0+00	754,393.310	3,030,230.300	--	--	Oregon Inlet	
47+85	750,431.033	3,032,912.951	2.139	P 194	Pea Island	Breach inlet (2011)
97+70	746,302.851	3,035,707.917	4.656	N 194	Pea Island	
421+10	715,494.663	3,045,543.459	4.397	NC 1230	CHN Seashore	Turning point
540+00	703,873.320	3,048,054.570	--	--	CHN Seashore	Turning point
548+94	703,011.000	3,048,292.000	--	--	CHN Seashore	Turning point
686+44	689,509.220	3,050,892.870	--	--	Rodanthe	North of pier
990+00	659,294.809	3,048,041.294	4.03	NC 1226	CHN Seashore	South of Salvo (No Ache Island)
1350+80	623,261.050	3,046,089.434	4.639	NC 1222	CHN Seashore	North of Avon (Drain Islands)
1821+84	576,613.697	3,039,543.710	5.306	NC 1218	Buxton	North of Development
1928+11	566,043.964	3,038,445.962	7.26	CHL 1	Buxton	Cape Hatteras Light (old site)
1983+77	560,711.538	3,036,849.925	1.312	BYRD	Cape Hatteras	North of Campground

ATTACHMENT 1B. CSE profile stations and azimuths (starting and ending points) used in August 2013 survey.

BUXTON			Start		End	
CSE Station	**Distance to Next**	**USACE Station**	**Easting**	**Northing**	**Easting**	**Northing**
1790+63	1,000	-	3039977.37	579704.14	3045424.01	578939.85
1800+63	1,000	-	3039838.41	578713.85	3045285.05	577949.55
1810+63	1,121	-	3039699.45	577723.55	3045146.09	576959.26
1821+84	879	-	3039543.71	576613.7	3045007.12	575968.96
1830+63	1,000	-	3039452.88	575739.13	3044923.45	575170.96
1840+63	1,000	-	3039349.58	574744.48	3044820.15	574176.31
1850+63	1,000	-	3039246.27	573749.83	3044716.85	573181.66
1860+63	1,000	-	3039142.97	572755.18	3044613.55	572187.01
1870+63	1,000	-	3039039.67	571760.53	3044510.25	571192.36
1880+63	1,000	-	3038936.37	570765.88	3044406.94	570197.71
1890+63	1,000	-	3038833.07	569771.23	3044303.64	569203.06
1900+63	1,000	-	3038729.76	568776.58	3044200.34	568208.41
1910+63	1,000	-	3038626.46	567781.93	3044097.04	567213.76
1920+63	748	-	3038523.16	566787.28	3043993.73	566219.11
1928+11	1,252	-	3038445.96	566043.96	3043760.07	564608.17
1940+63	1,000	-	3038086.76	564843.88	3043355.81	563266.8
1950+63	1,000	-	3037800.02	563885.87	3043069.07	562308.8
1960+63	1,000	-	3037513.28	562927.86	3042782.33	561350.79
1970+63	1,314	-	3037226.54	561969.85	3042495.59	560392.78
1983+77	-	-	3036849.92	560711.54	3042306.69	559997.55

ATTACHMENT 1C. Station coordinates for the October 2014 survey.

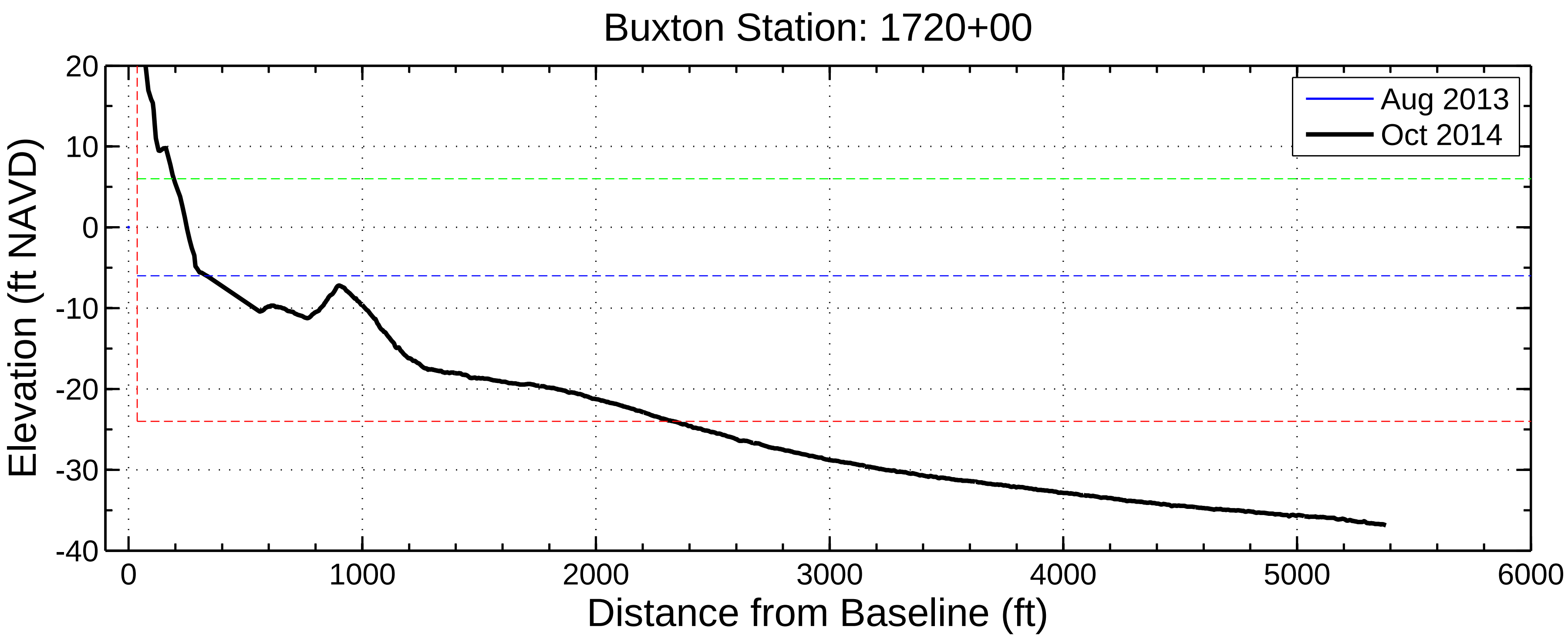
BUXTON		Start		End	
CSE Station	Distance to Next	Easting	Northing	Easting	Northing
1720+00	500	3040958.91	586698.98	3046405.55	585934.69
1725+00	500	3040889.43	586203.83	3046336.07	585439.54
1730+00	500	3040819.95	585708.68	3046266.59	584944.39
1735+00	500	3040750.47	585213.53	3046197.11	584449.24
1740+00	500	3040680.99	584718.38	3046127.63	583954.09
1745+00	500	3040611.51	584223.24	3046058.14	583458.94
1750+00	500	3040542.03	583728.09	3045988.66	582963.80
1755+00	500	3040472.54	583232.94	3045919.18	582468.65
1760+00	500	3040403.06	582737.79	3045849.70	581973.50
1765+00	500	3040333.58	582242.64	3045780.22	581478.35
1770+00	500	3040264.10	581747.49	3045710.74	580983.20
1775+00	500	3040194.62	581252.34	3045641.26	580488.05
1780+00	500	3040125.14	580757.19	3045571.78	579992.90
1785+00	500	3040055.66	580262.05	3045502.30	579497.75
1790+00	500	3039986.18	579766.90	3045432.81	579002.61
1795+00	500	3039916.70	579271.75	3045363.33	578507.46
1800+00	500	3039847.22	578776.60	3045293.85	578012.31
1805+00	500	3039777.73	578281.45	3045224.37	577517.16
1810+00	500	3039708.25	577786.30	3045154.89	577022.01
1815+00	500	3039638.77	577291.15	3045085.41	576526.86
1820+00	500	3039569.29	576796.00	3045015.93	576031.71
1825+00	500	3039511.08	576299.48	3044981.65	575731.32
1830+00	500	3039459.42	575802.15	3044930.00	575233.99
1835+00	500	3039407.77	575304.83	3044878.35	574736.67
1840+00	500	3039356.12	574807.50	3044826.70	574239.34
1845+00	500	3039304.47	574310.18	3044775.05	573742.02
1850+00	500	3039252.82	573812.85	3044723.40	573244.69
1855+00	500	3039201.17	573315.53	3044671.74	572747.37
1860+00	500	3039149.52	572818.20	3044620.09	572250.04
1865+00	500	3039097.87	572320.88	3044568.44	571752.72
1870+00	500	3039046.22	571823.55	3044516.79	571255.39
1875+00	500	3038994.56	571326.23	3044465.14	570758.07
1880+00	500	3038942.91	570828.90	3044413.49	570260.74
1885+00	500	3038891.26	570331.58	3044361.84	569763.42
1890+00	500	3038839.61	569834.25	3044310.19	569266.09
1895+00	500	3038787.96	569336.93	3044258.54	568768.77
1900+00	500	3038736.31	568839.60	3044206.88	568271.44
1905+00	500	3038684.66	568342.28	3044155.23	567774.12
1910+00	500	3038633.01	567844.95	3044103.58	567276.79
1915+00	500	3038581.36	567347.63	3044051.93	566779.47
1920+00	500	3038529.71	566850.30	3044000.28	566282.14
1925+00	500	3038478.05	566352.98	3043948.63	565784.82
1930+00	500	3038391.67	565862.59	3043660.72	564285.52
1935+00	500	3038248.30	565383.59	3043517.35	563806.52
1940+00	500	3038104.93	564904.58	3043373.98	563327.51
1945+00	500	3037961.56	564425.58	3043230.61	562848.51
1950+00	500	3037818.19	563946.57	3043087.24	562369.50
1955+00	500	3037674.82	563467.57	3042943.87	561890.50
1960+00	500	3037531.45	562988.57	3042800.50	561411.49
1965+00	500	3037388.08	562509.56	3042657.13	560932.49
1970+00	500	3037244.71	562030.56	3042513.76	560453.49
1975+00	500	3037101.34	561551.55	3042370.39	559974.48
1980+00	500	3036957.97	561072.55	3042227.02	559495.48

ATTACHMENT 2

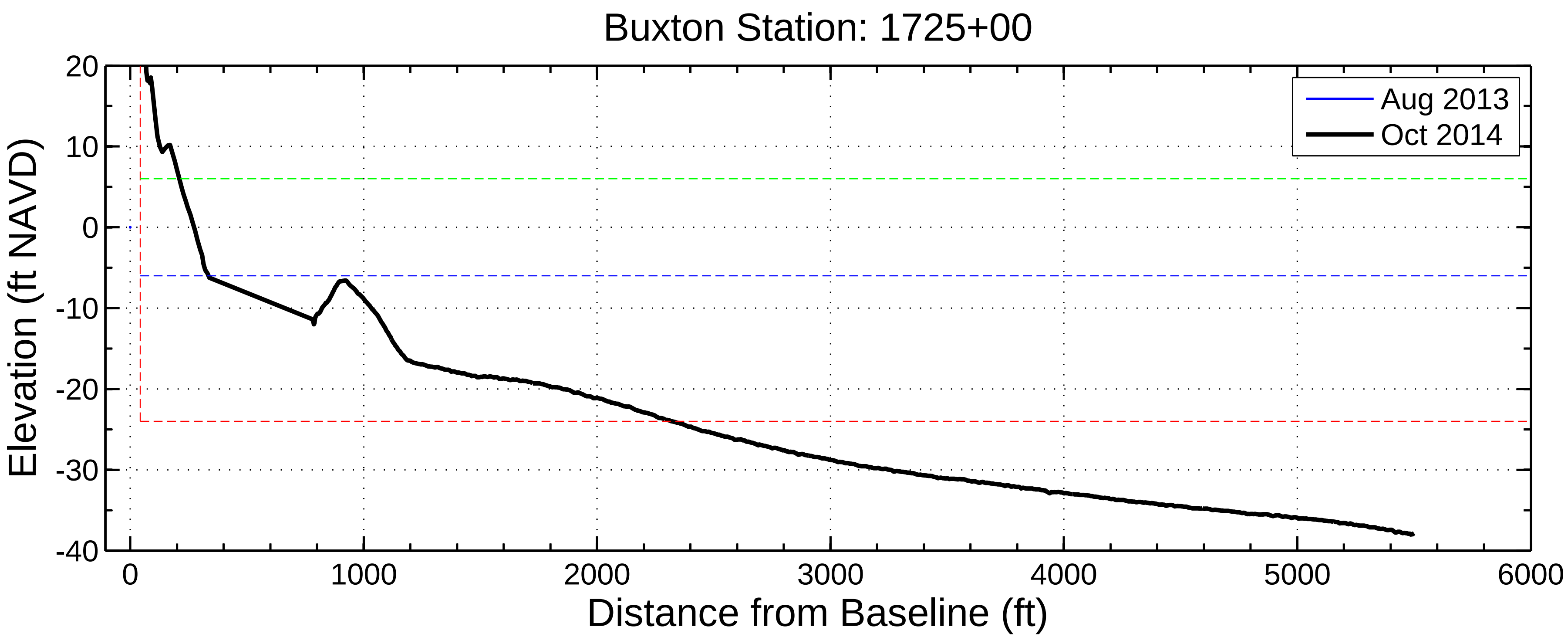
Beach & Inshore Profiles

ATTACHMENT 2

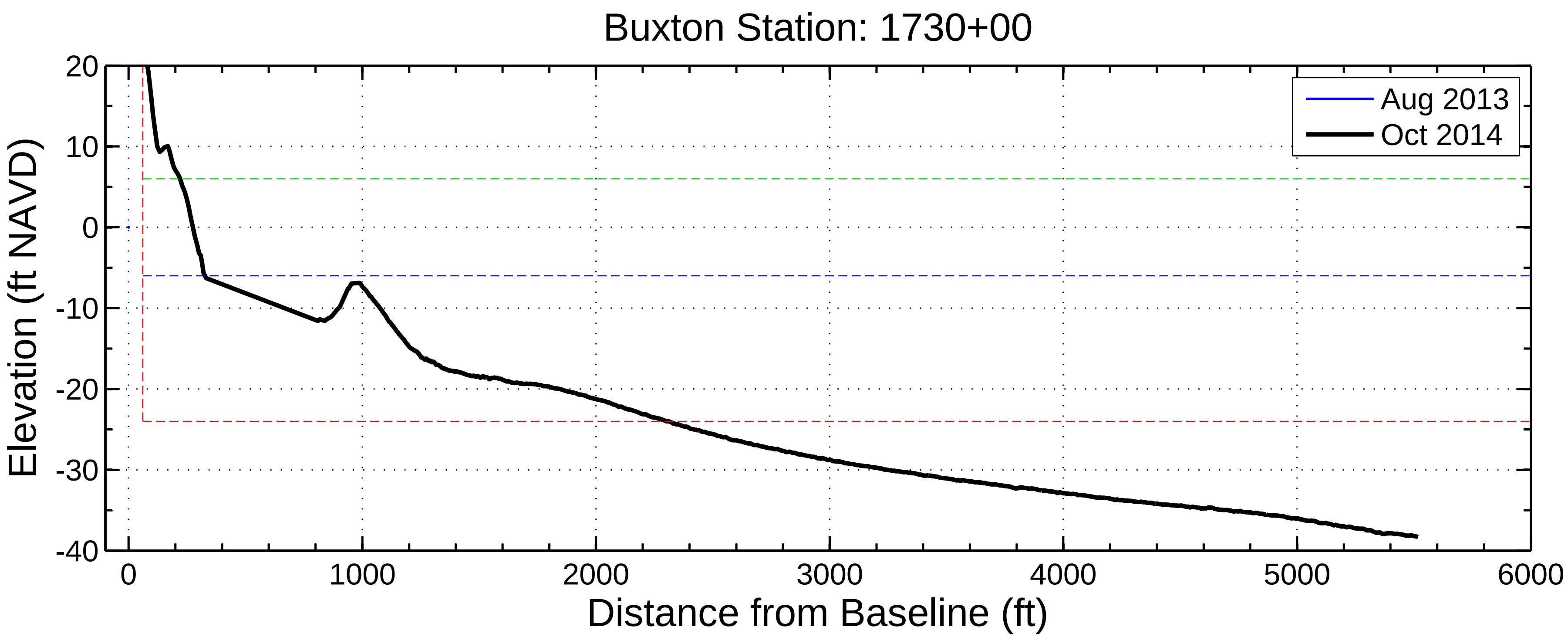
Beach & Inshore Profiles



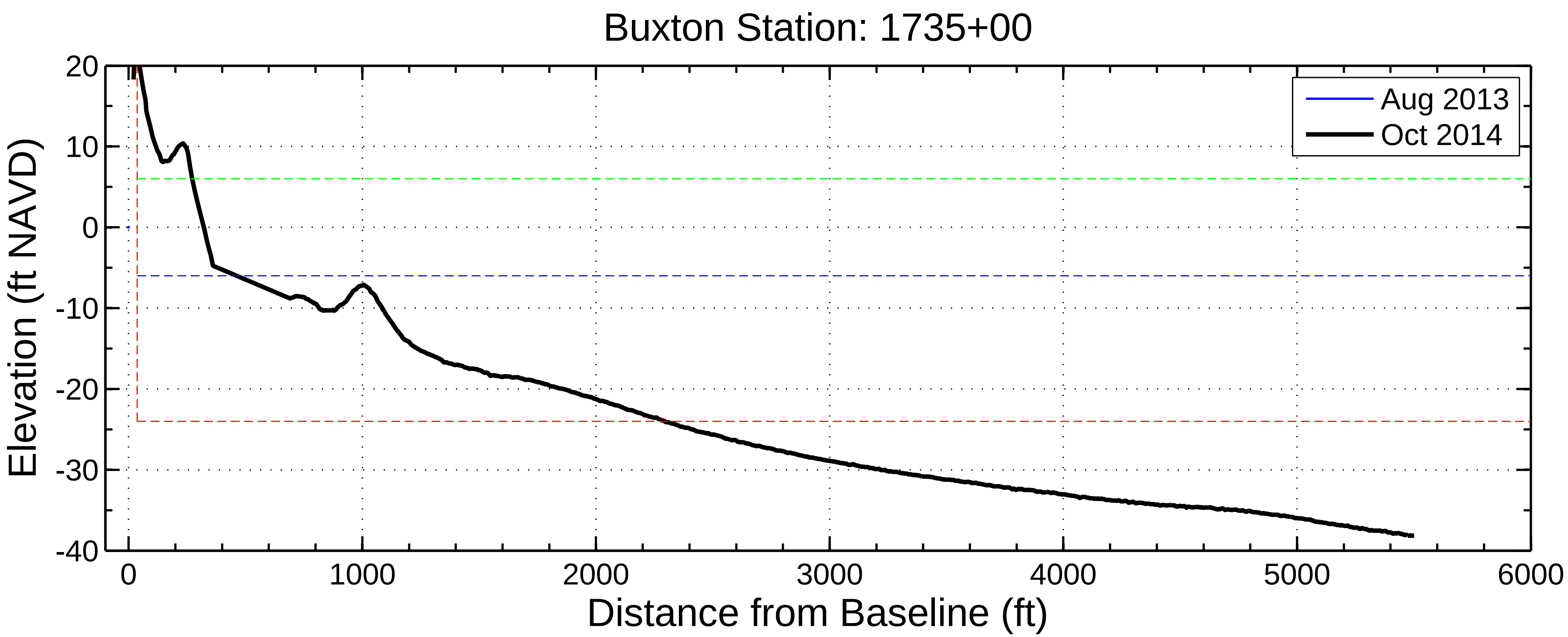
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	52.7	147.9	960.0



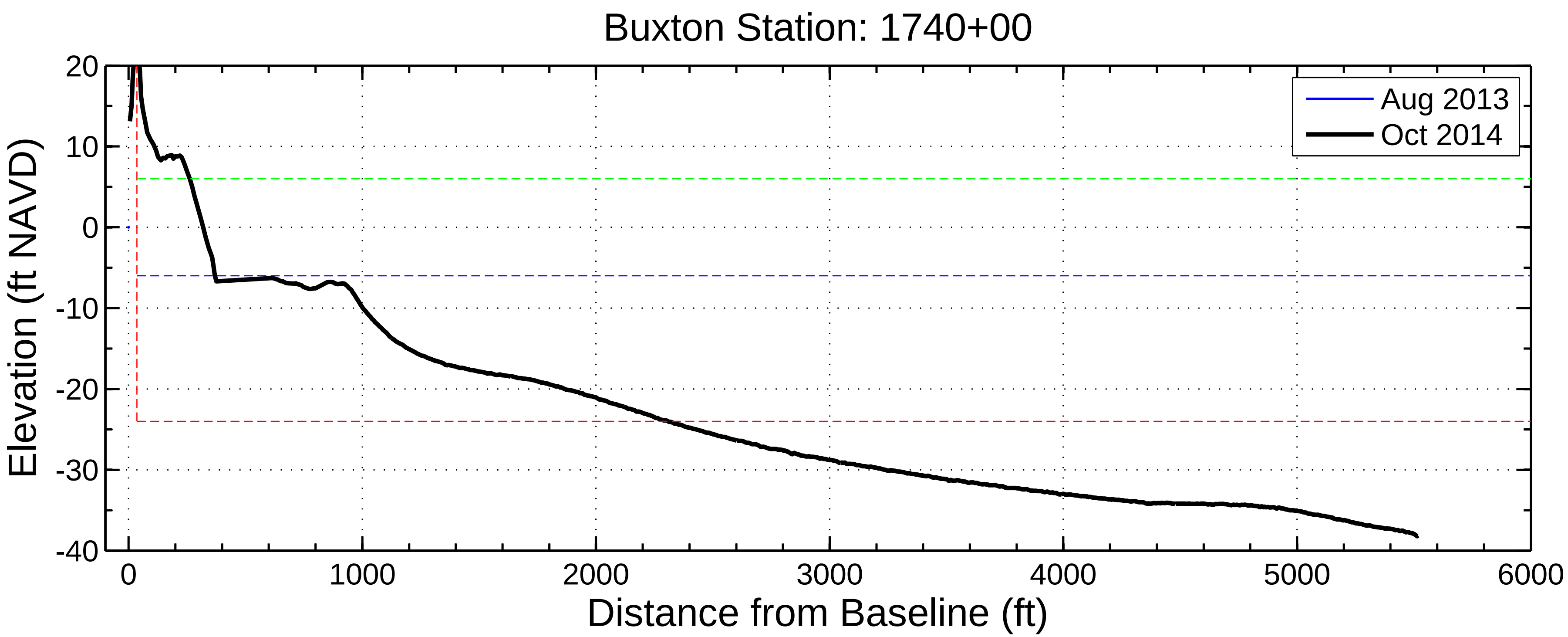
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	48.5	149.8	976.0



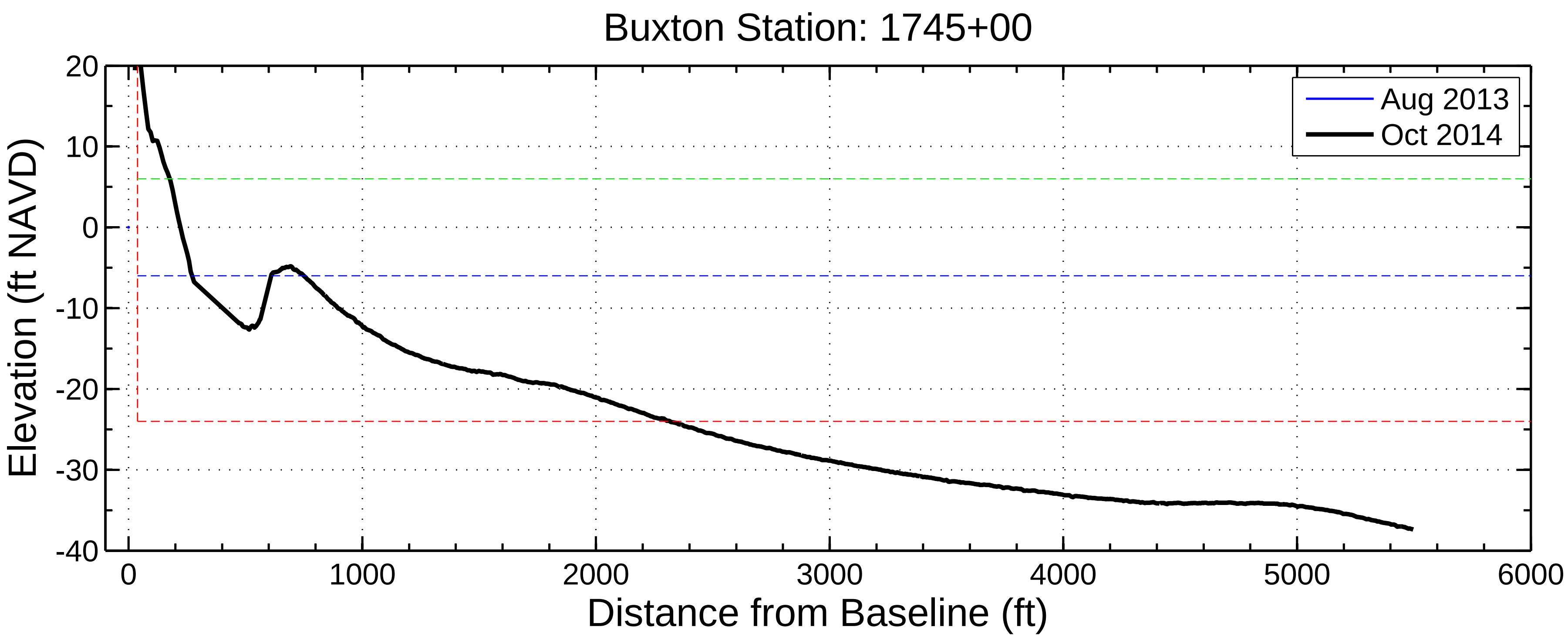
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	36.6	132.5	952.2



Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	44.8	173.6	1054.2



Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	37.2	163.3	1052.4



Date	Vol to +6	Vol to -6	Vol to -24
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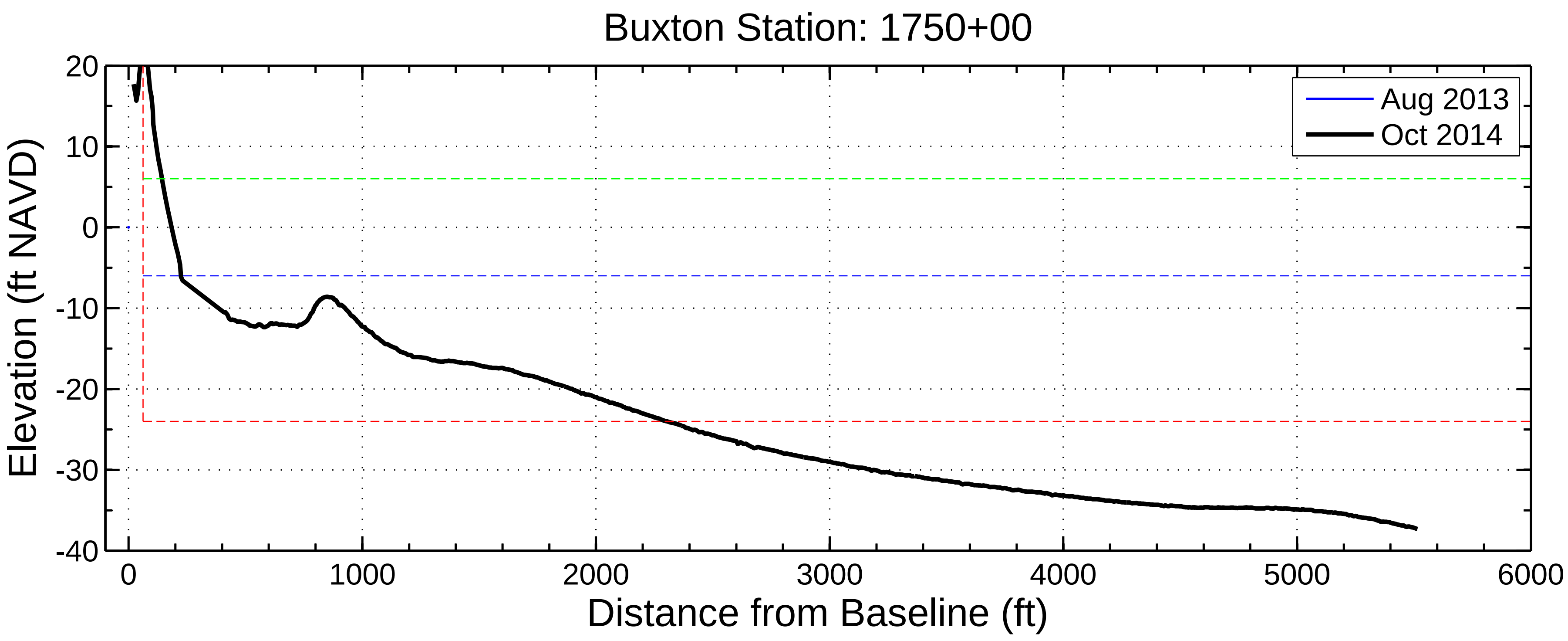

Date	Vol to +6	Vol to -6	Vol to -24
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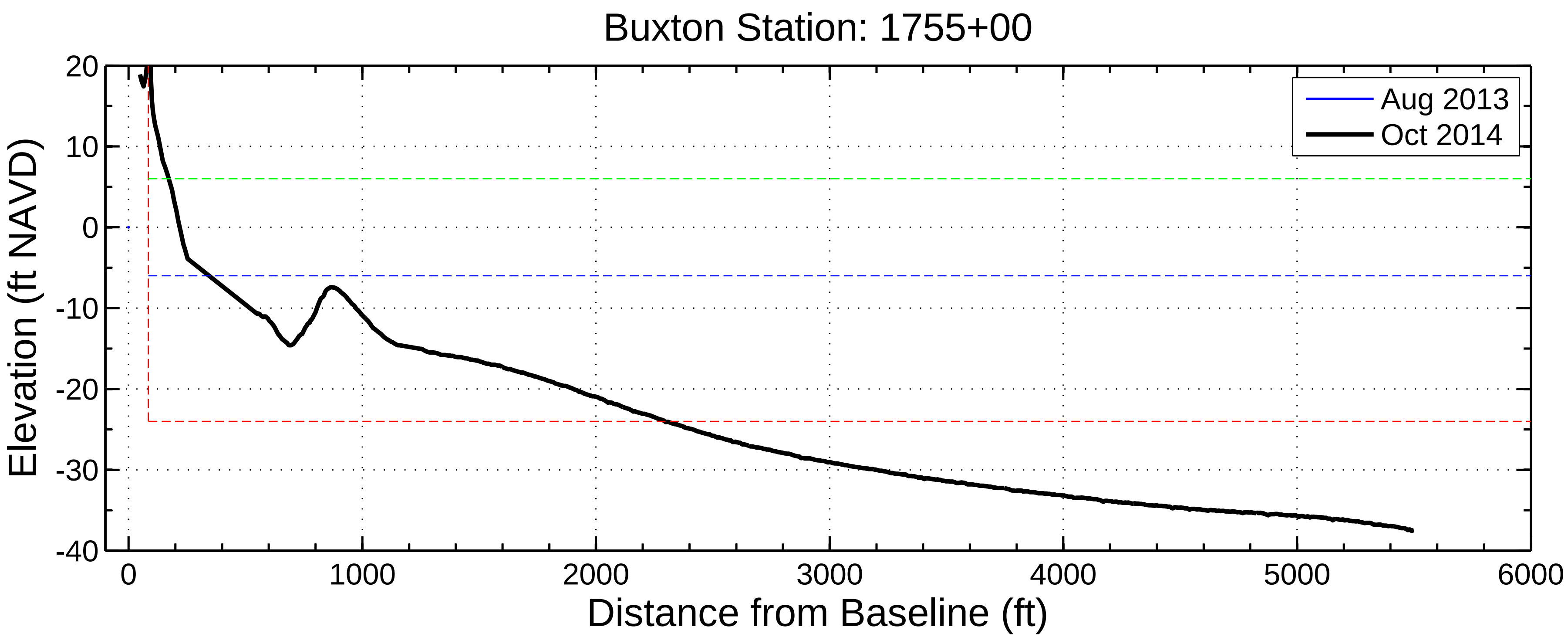
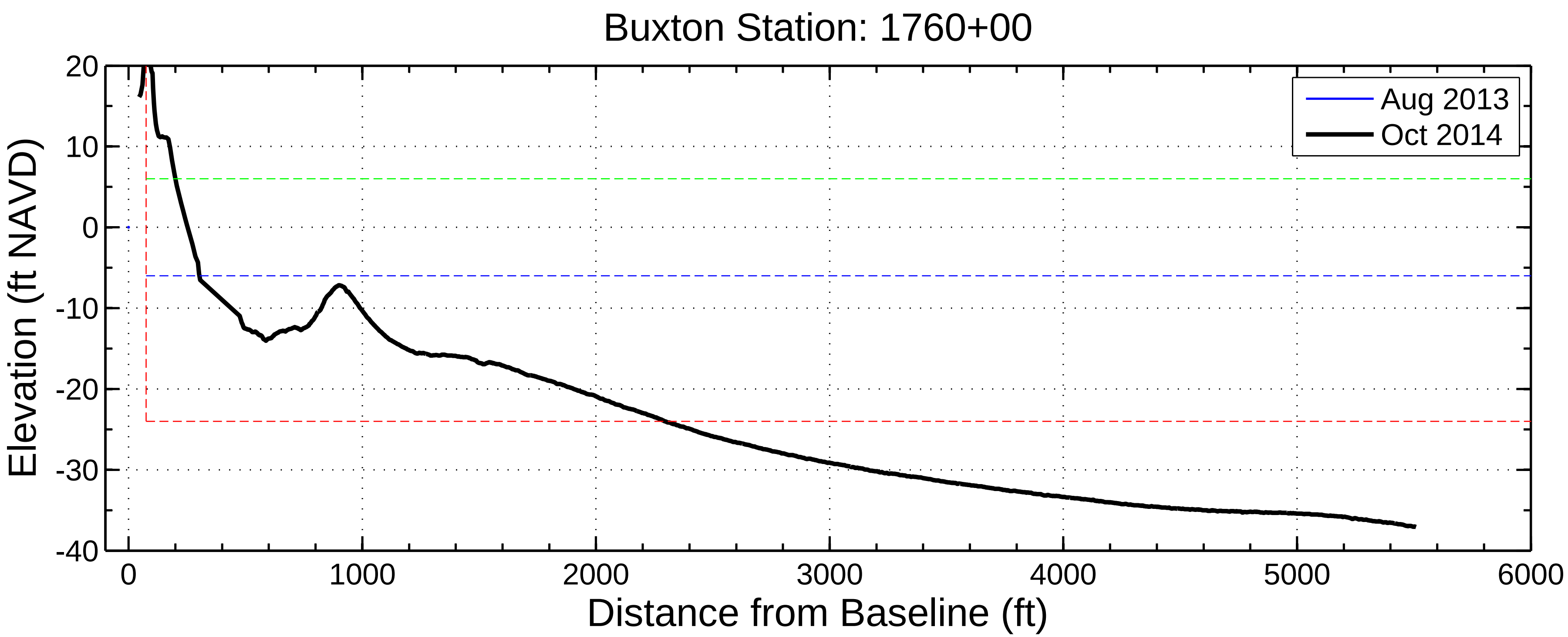
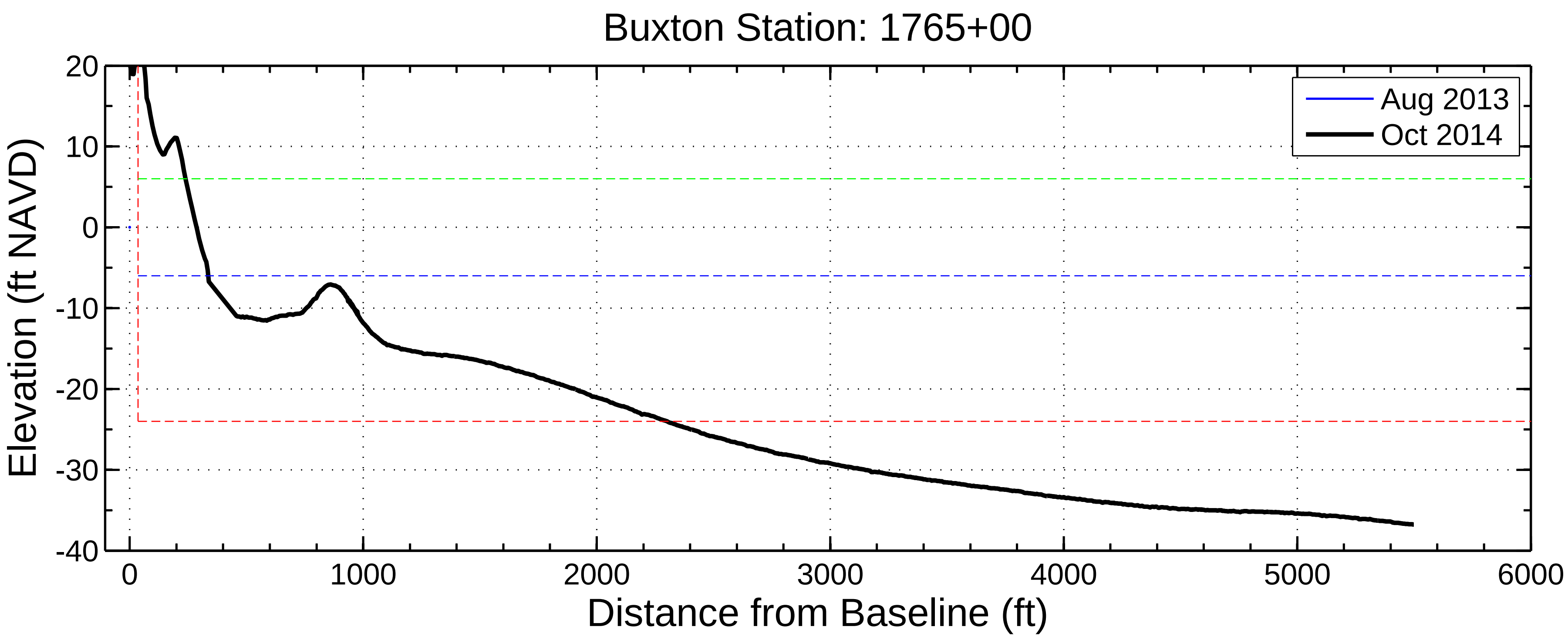


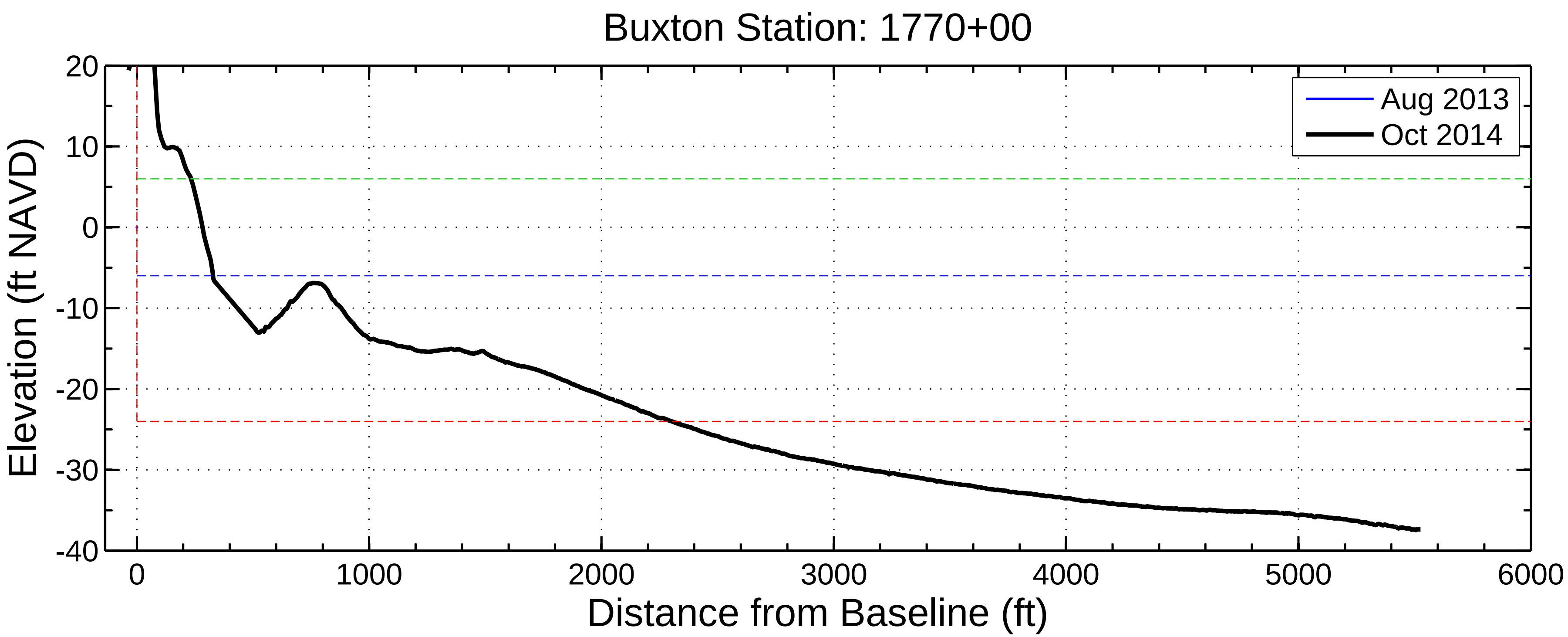
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	18.7	82.0	879.2



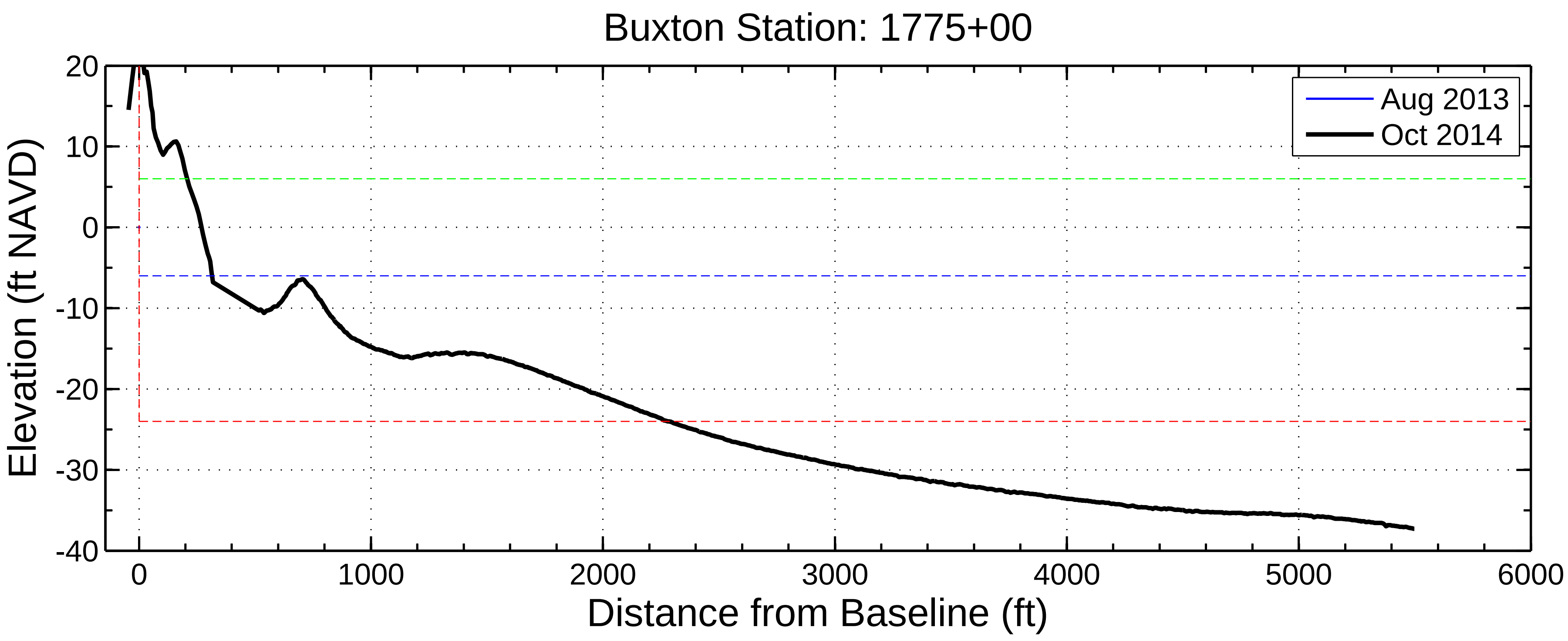
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	33.0	112.1	897.9



Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	48.8	161.0	990.9

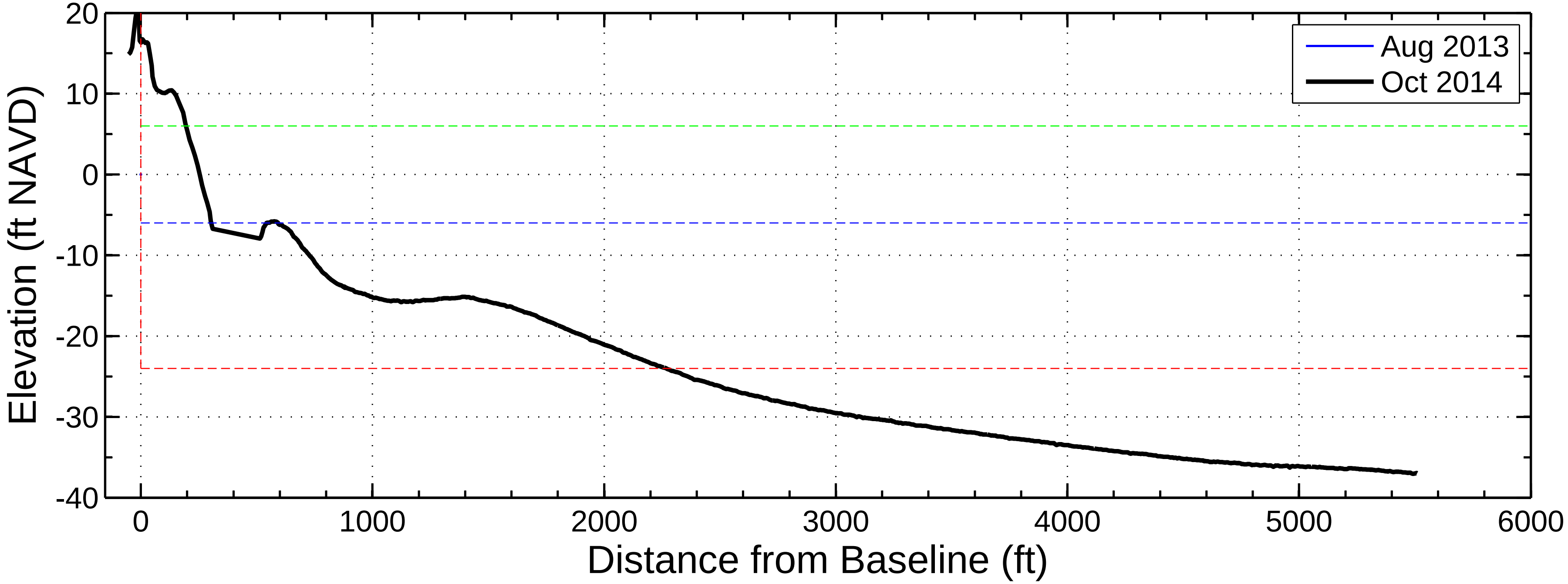


Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	70.7	196.6	1058.4



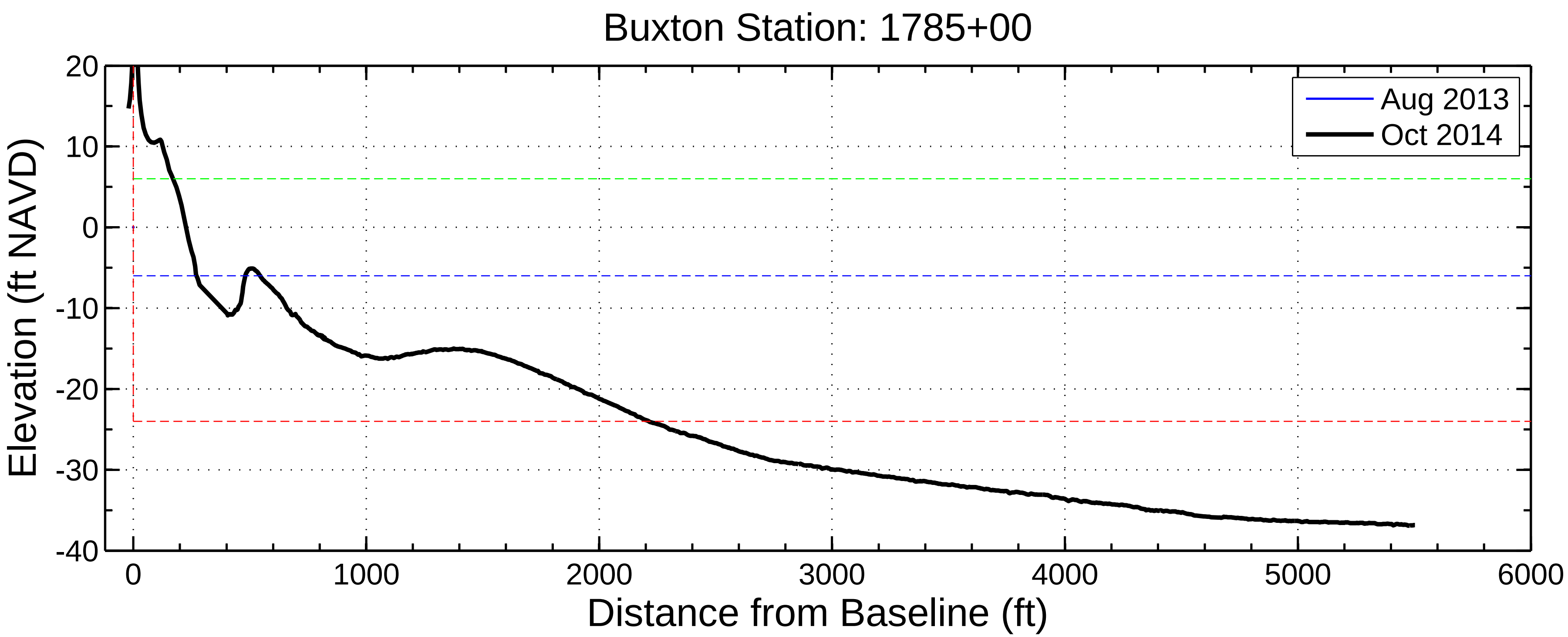
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	49.7	168.6	1017.0

Buxton Station: 1780+00

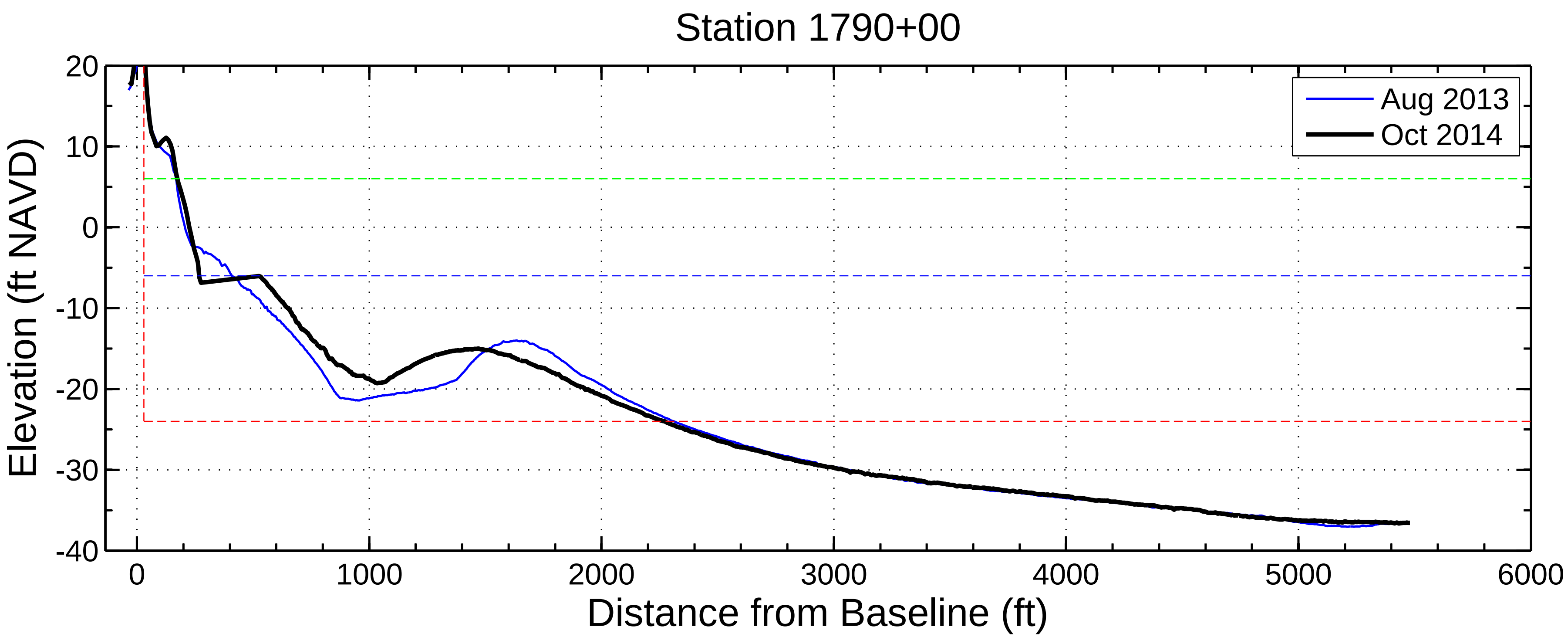


Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	38.0	150.6	1003.3

Buxton Station: 1785+00

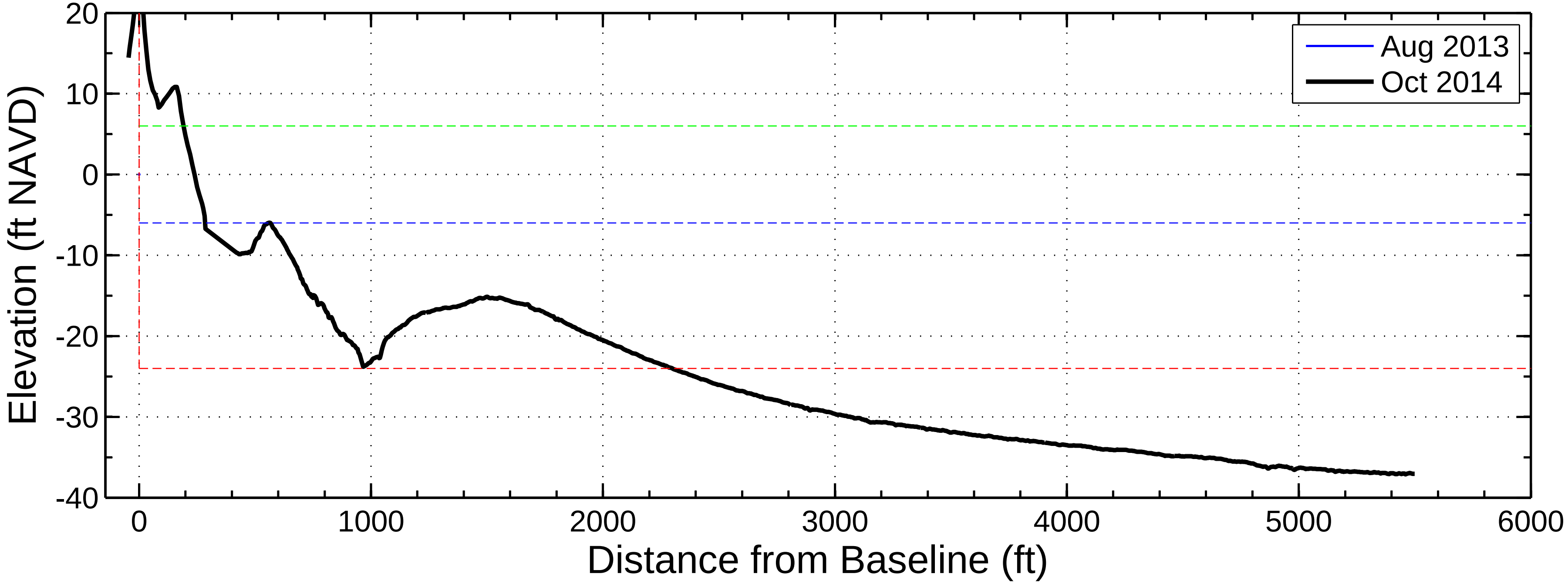


Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	38.1	140.0	956.5



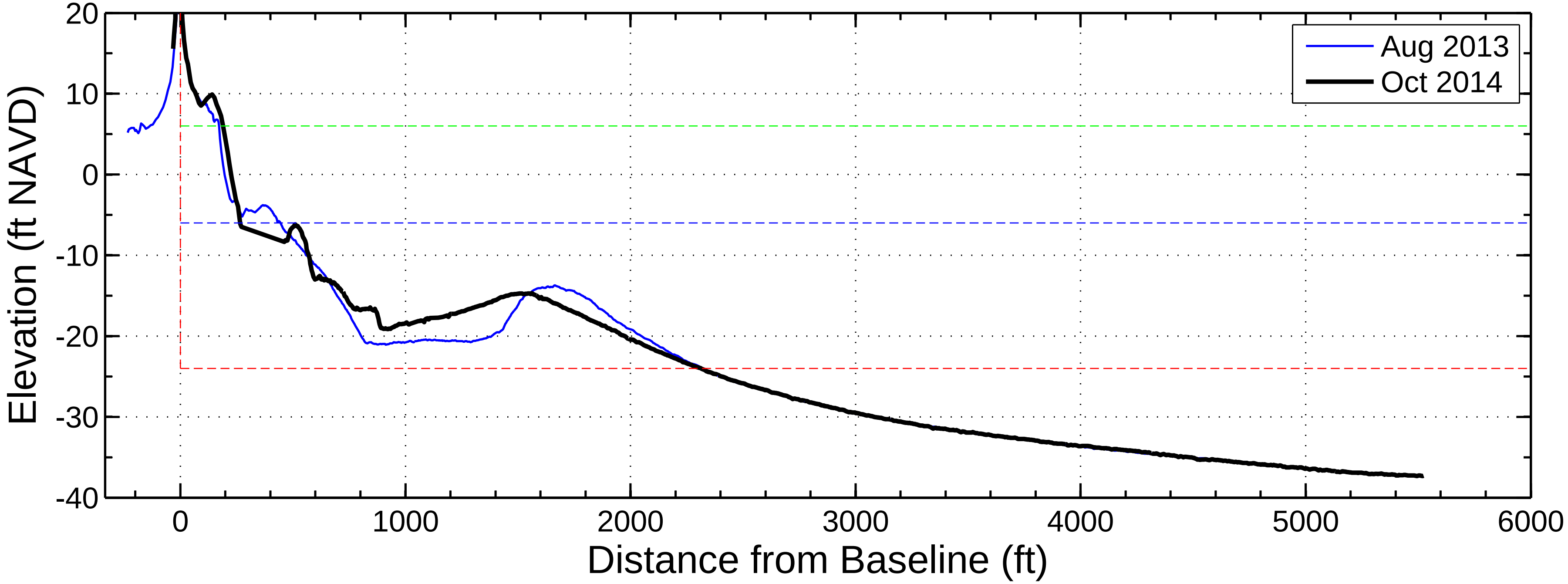
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	27.0	120.7	838.3
Oct 2014	28.8	115.6	894.4

Buxton Station: 1795+00

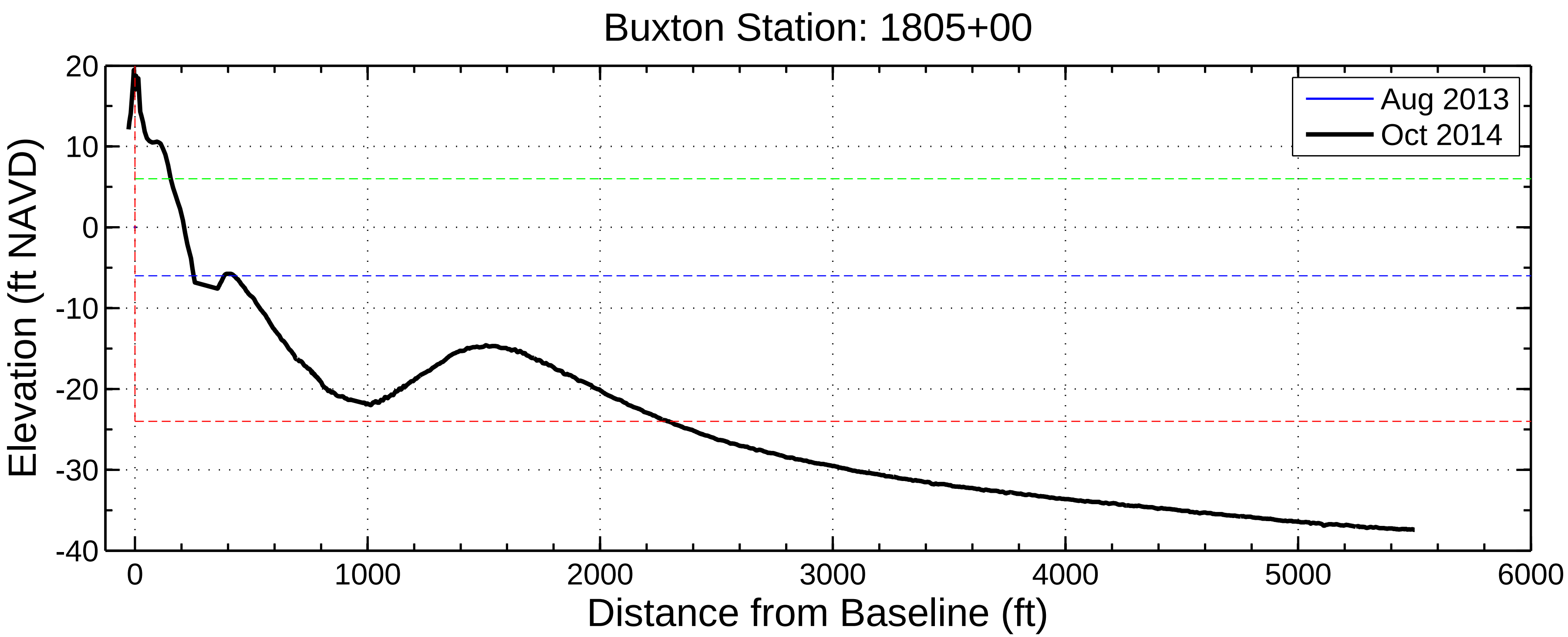


Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	41.4	148.0	891.3

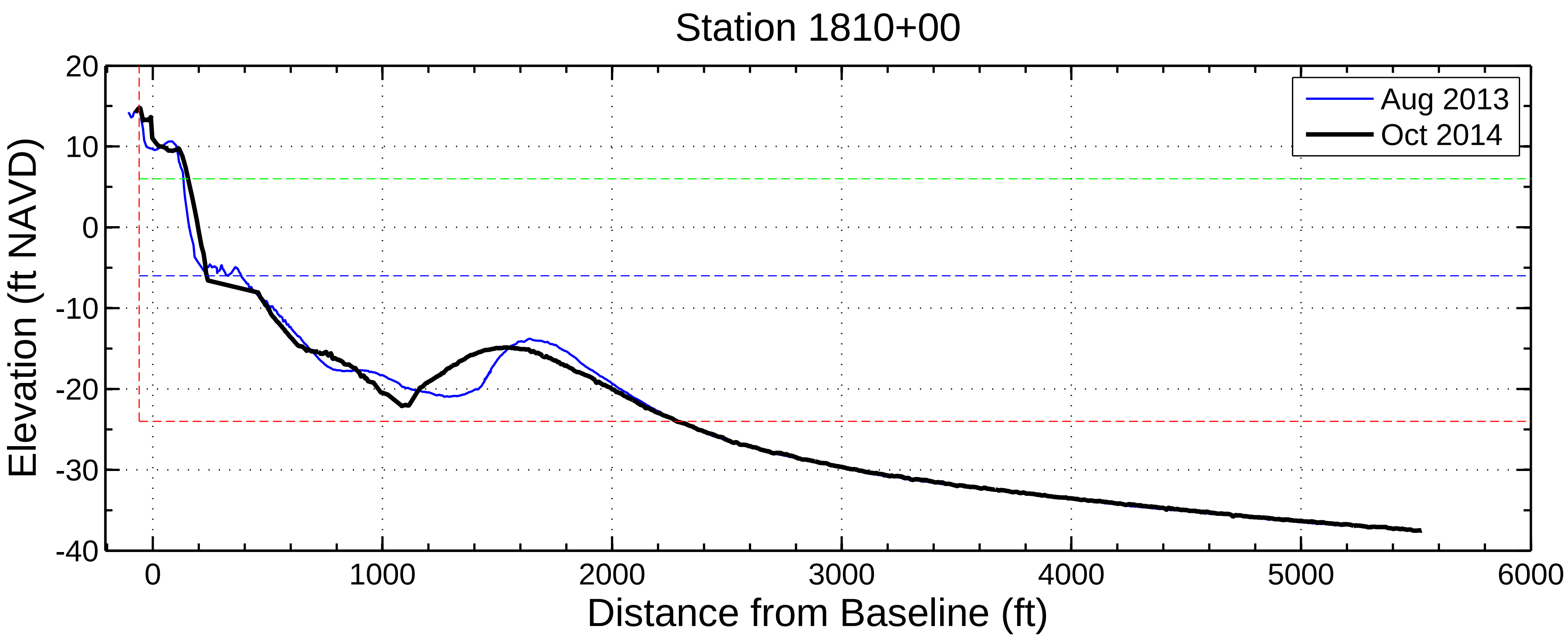
Station 1800+00



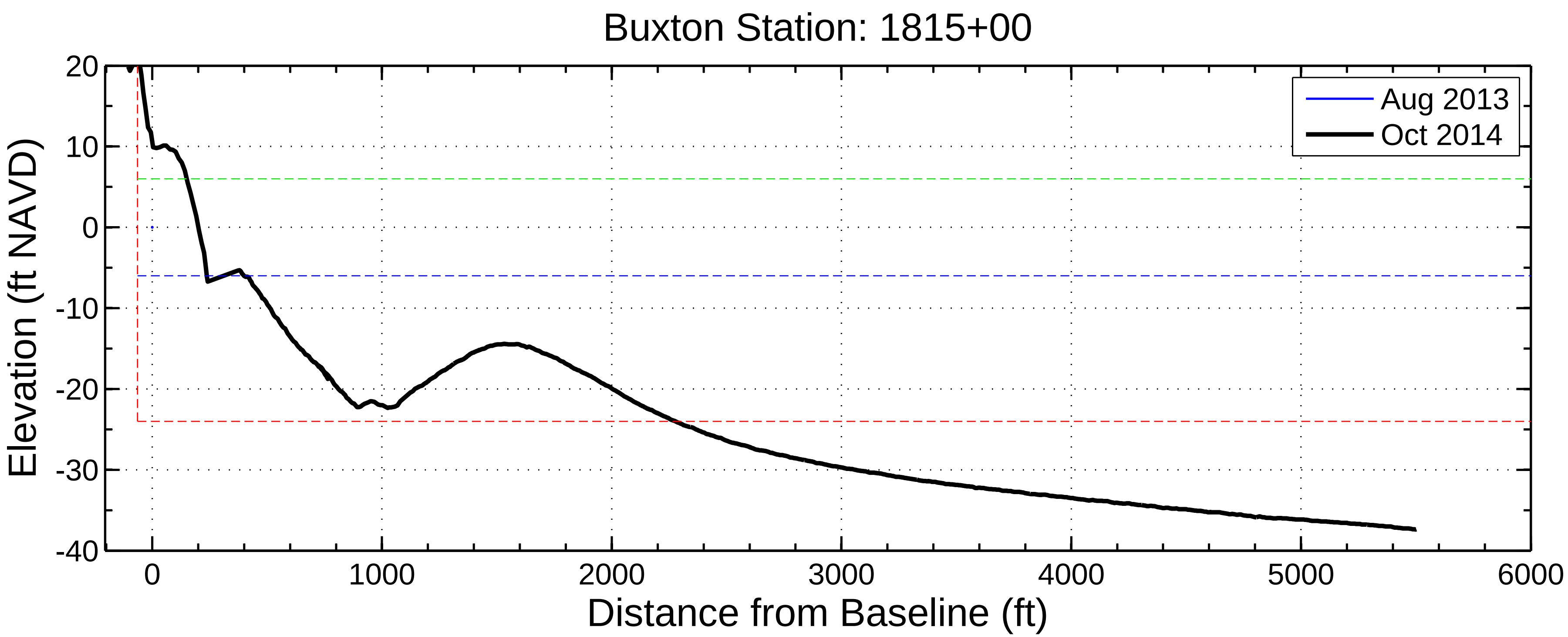
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	30.7	132.5	862.1
Oct 2014	34.1	135.1	909.4



Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	31.0	124.1	841.1

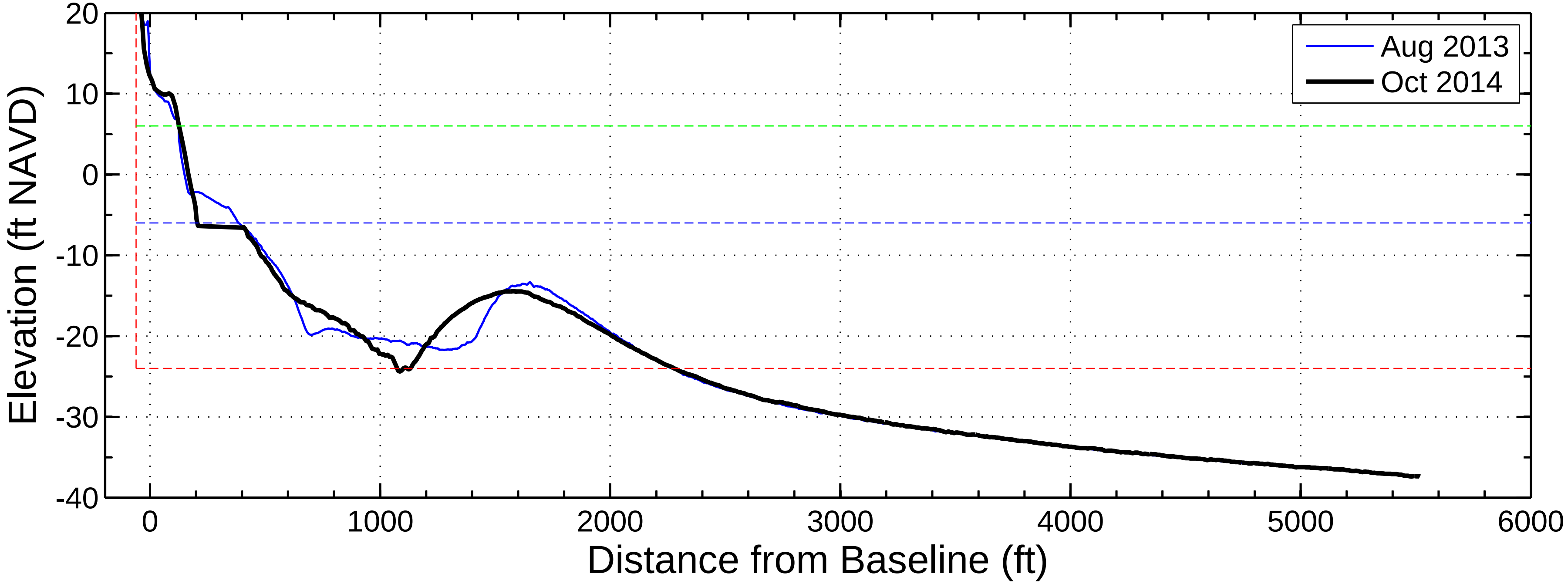


Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	29.4	133.9	910.8
Oct 2014	35.9	149.8	918.9

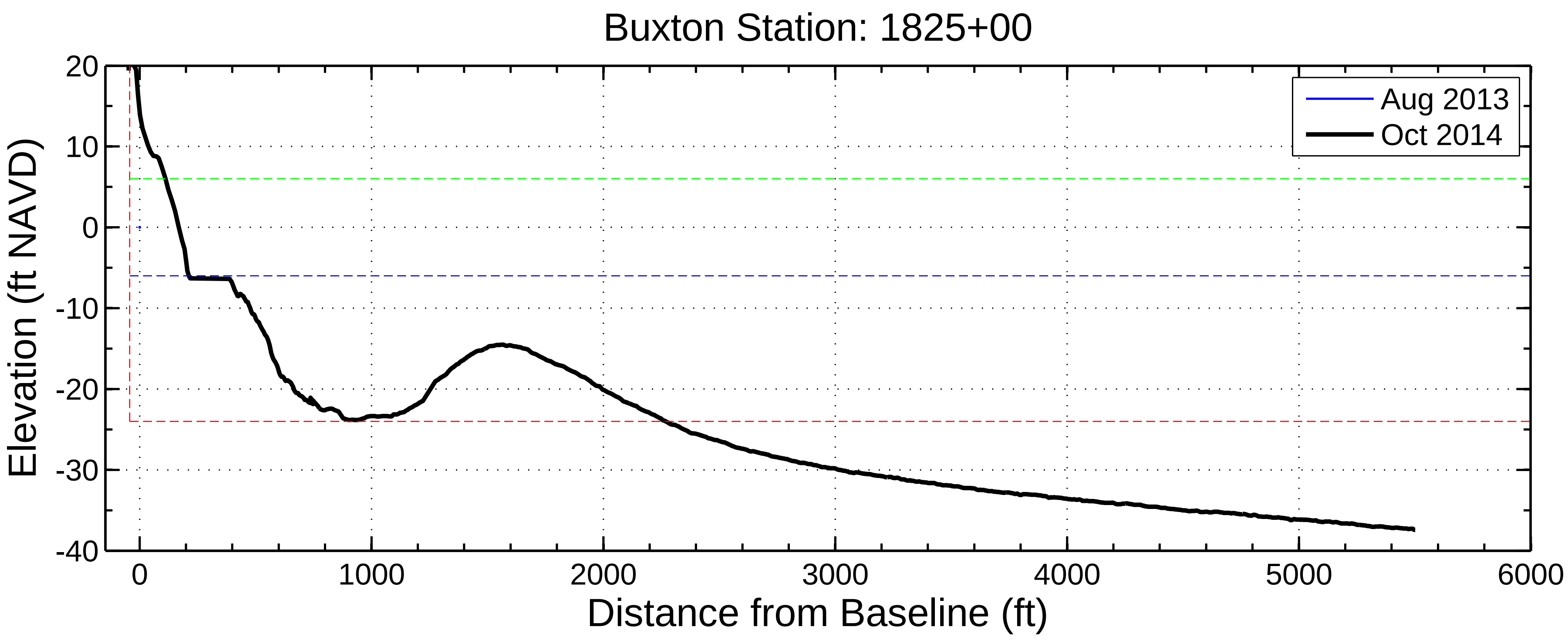


Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	41.0	159.2	914.1

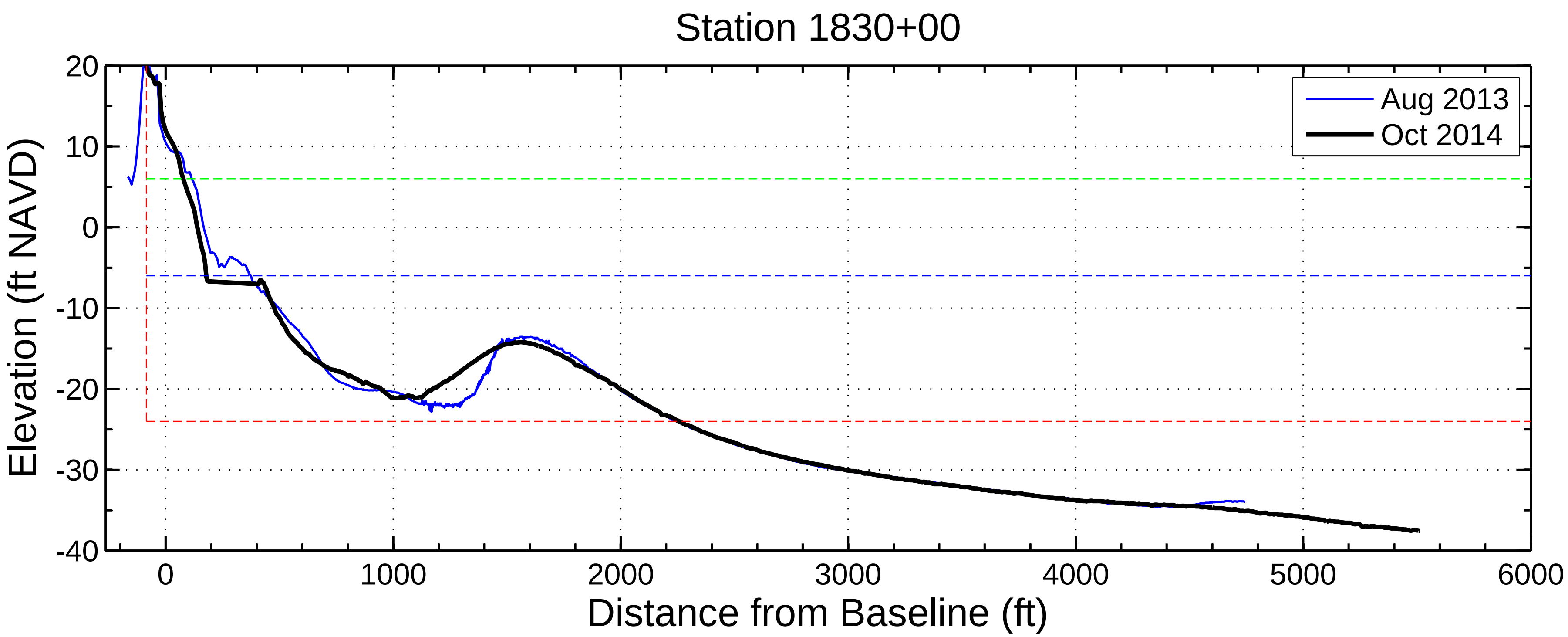
Station 1820+00



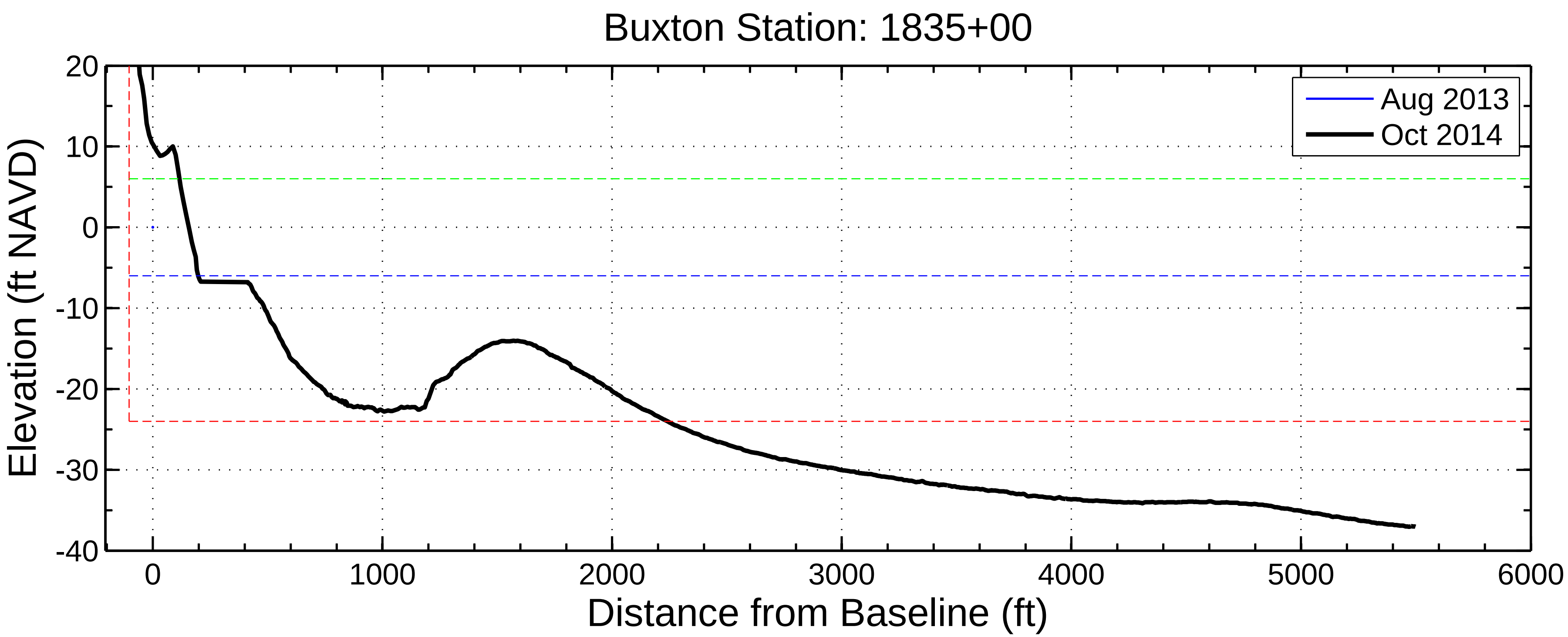
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	44.1	158.2	885.8
Oct 2014	42.8	144.2	880.2



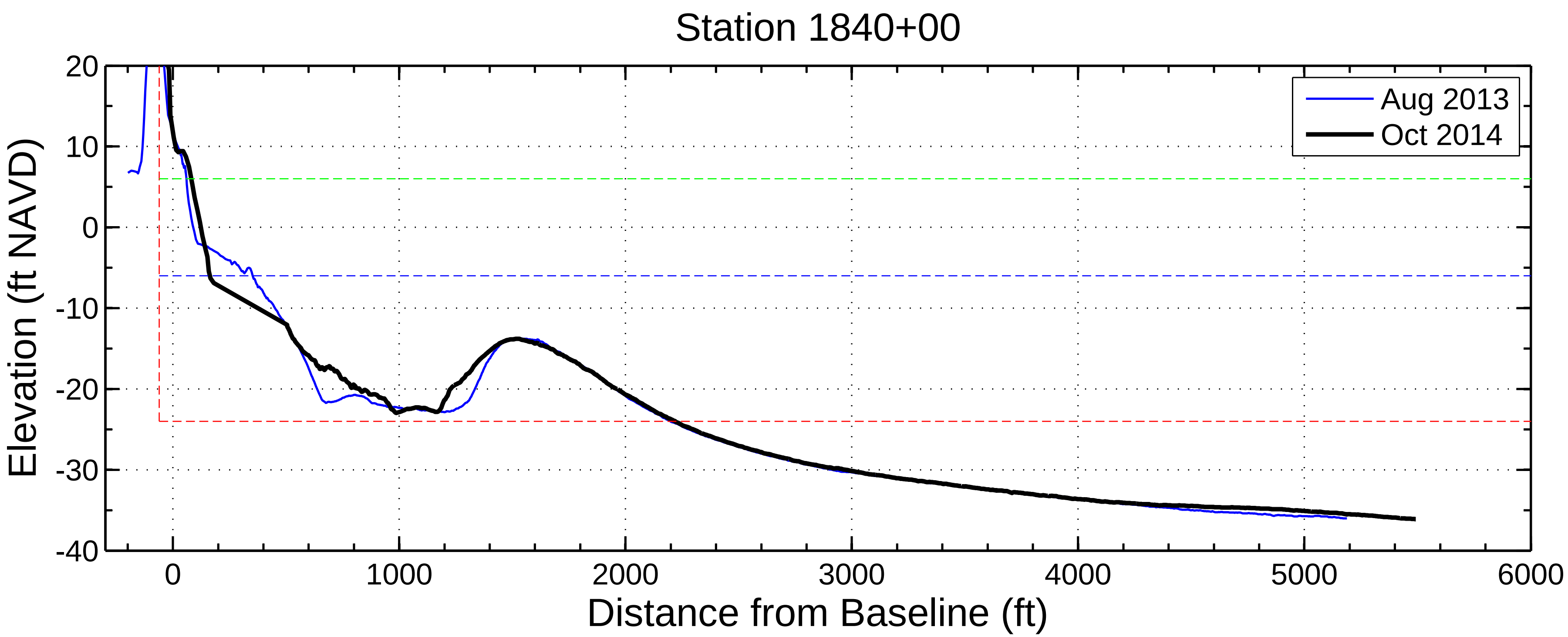
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	35.7	129.2	779.1



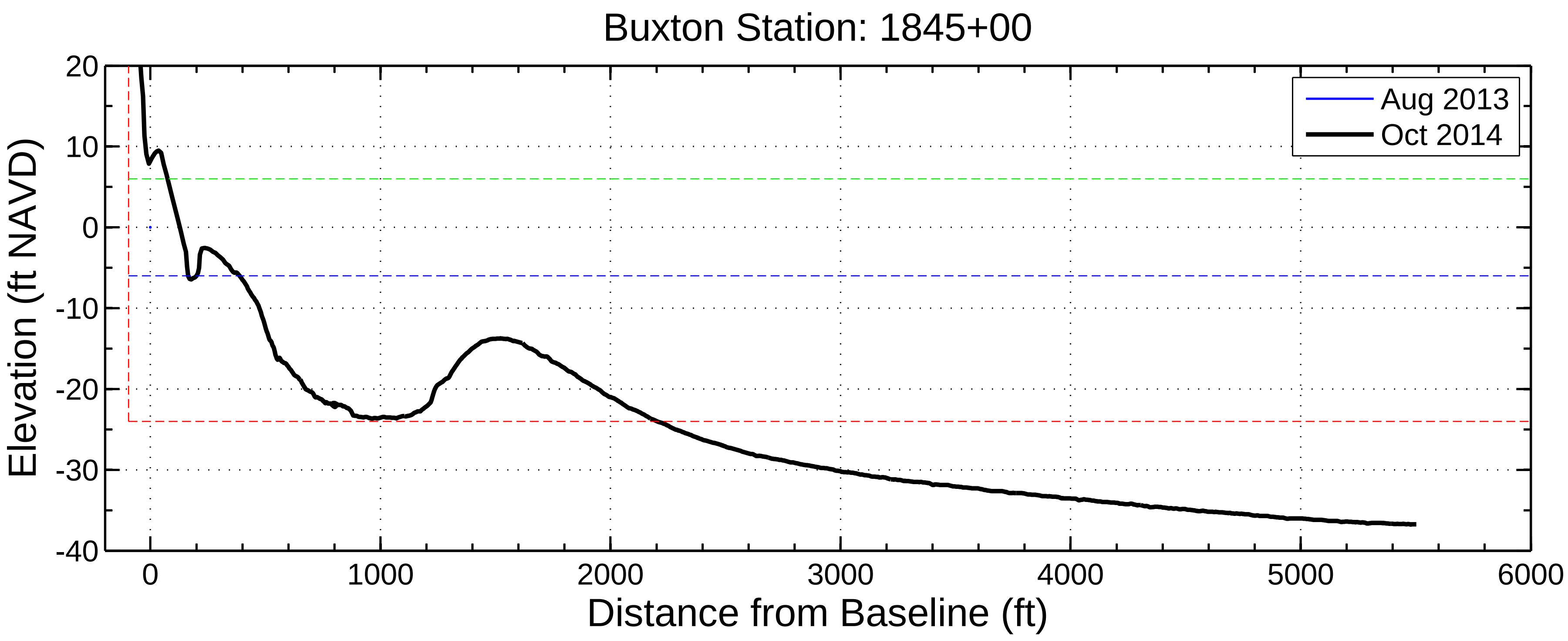
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	43.5	166.7	909.4
Oct 2014	44.5	143.0	904.1



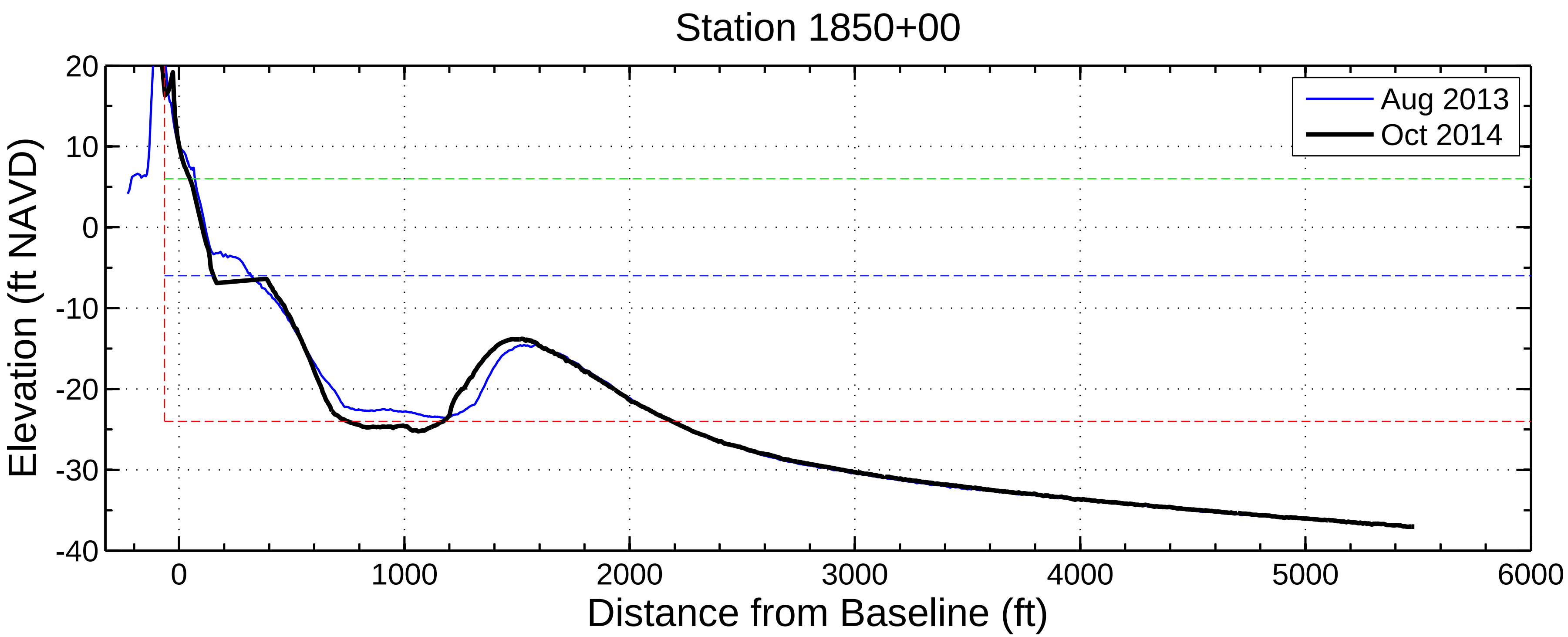
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	63.4	178.8	905.9



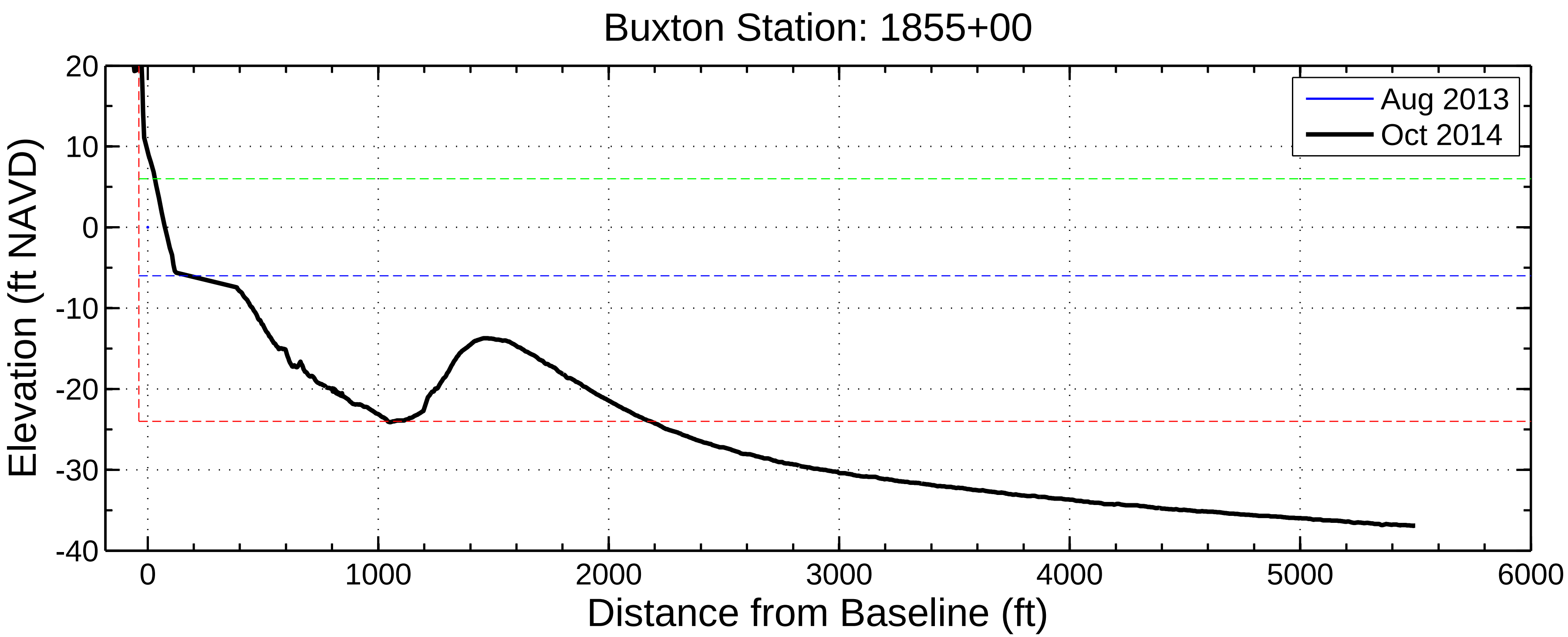
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	31.7	117.7	770.2
Oct 2014	39.2	120.7	797.3



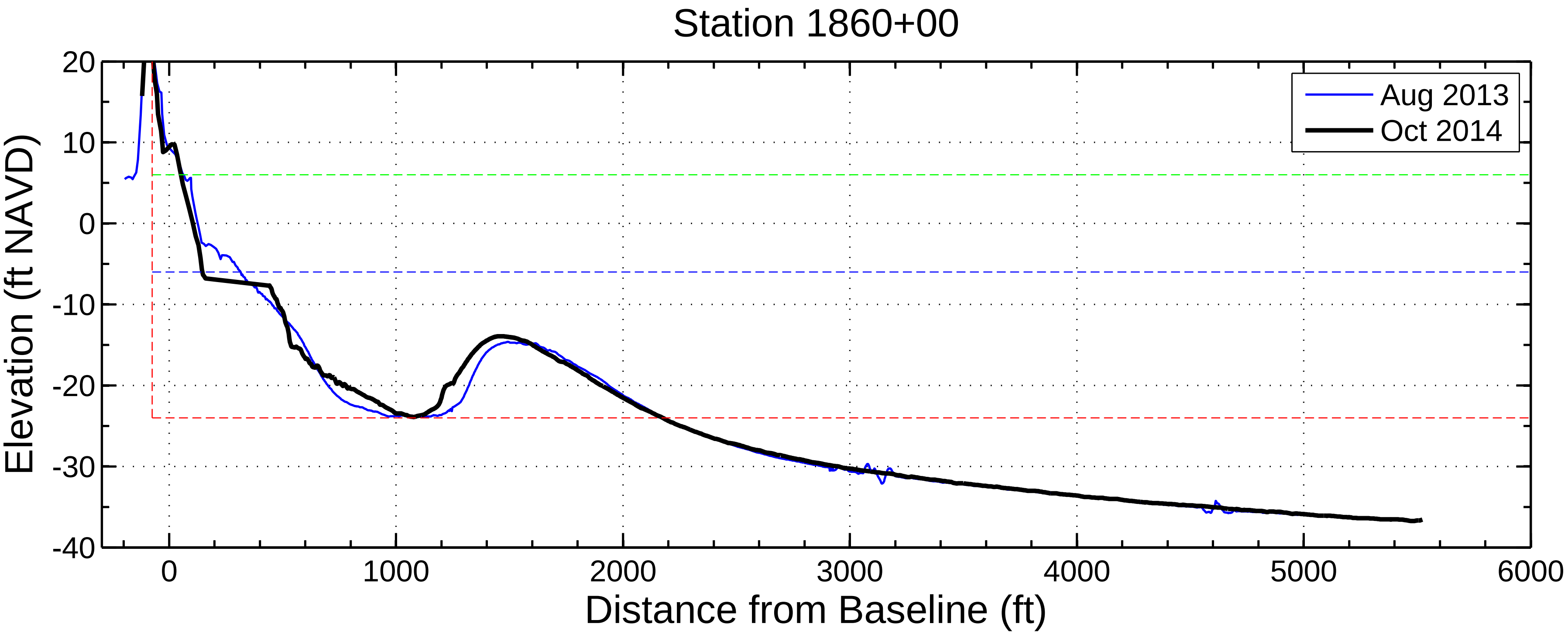
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	47.5	159.2	841.7



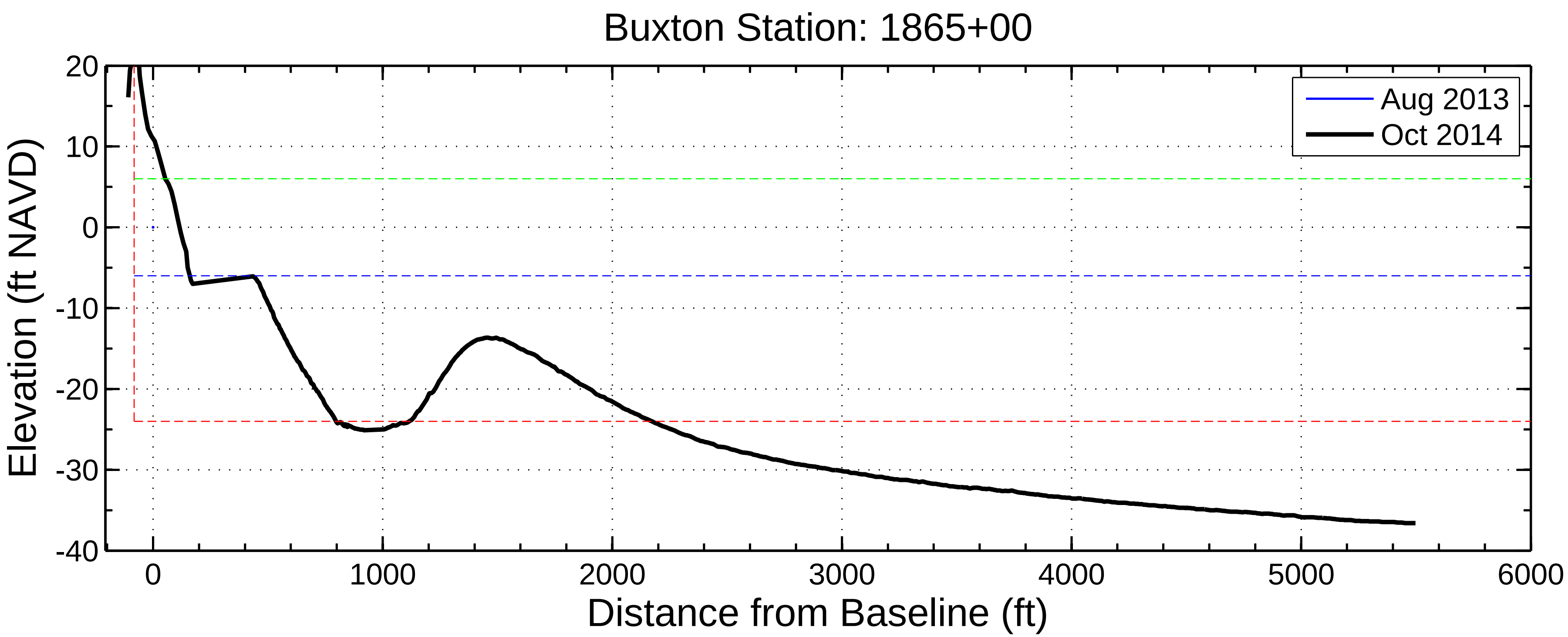
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	27.2	120.7	744.9
Oct 2014	26.2	100.7	722.5



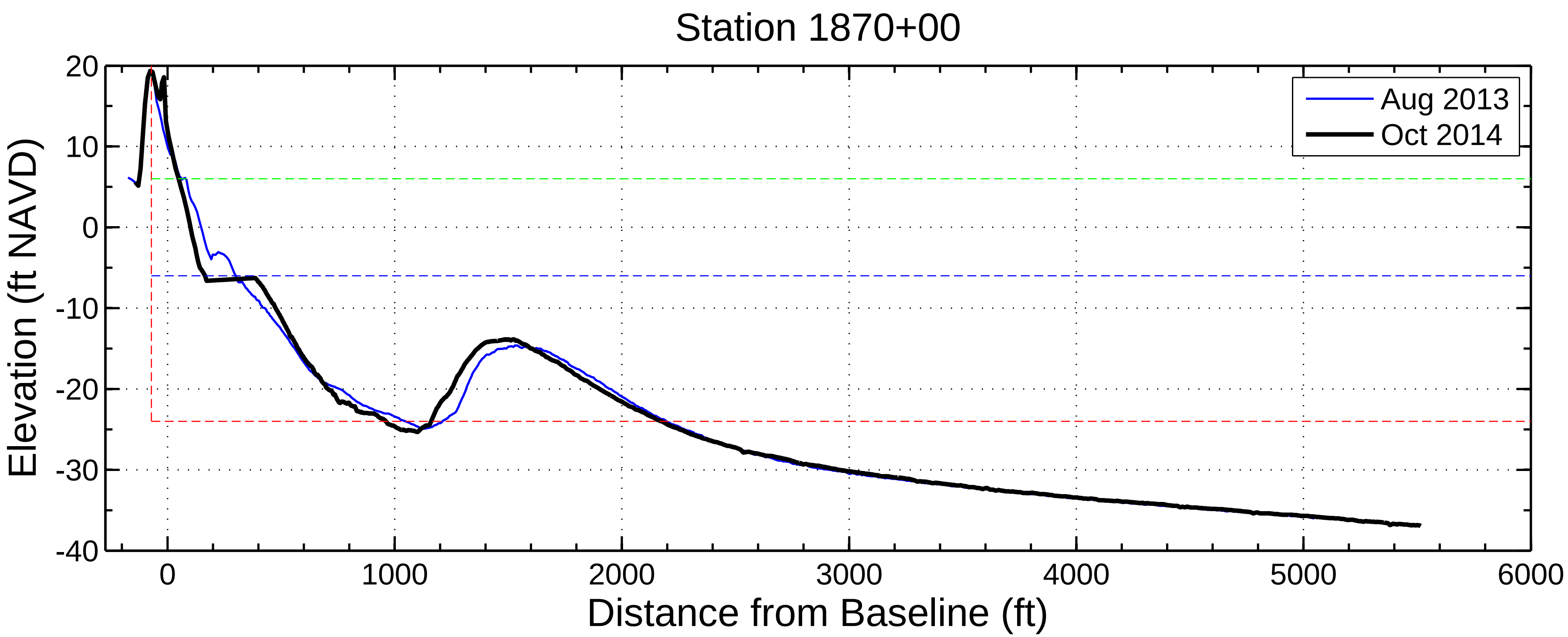
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	14.7	66.0	718.4



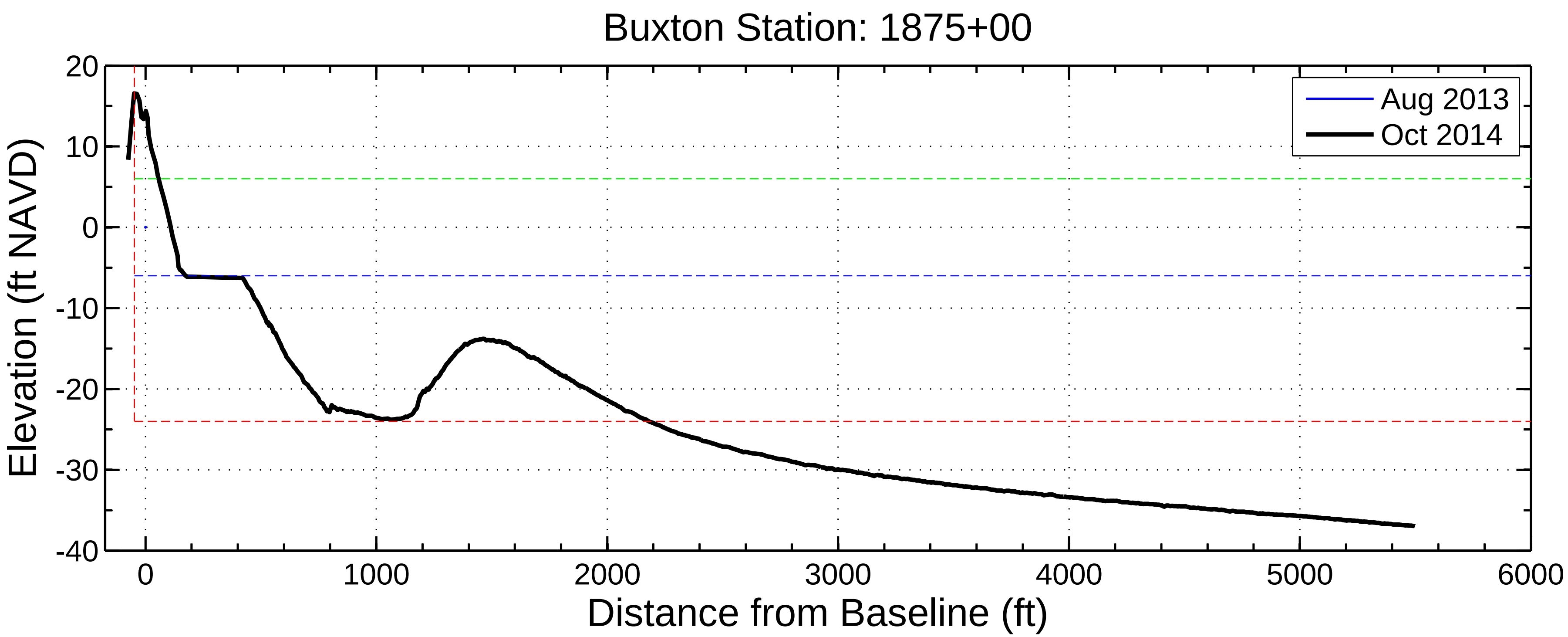
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	29.7	131.3	771.8
Oct 2014	24.3	103.4	774.4



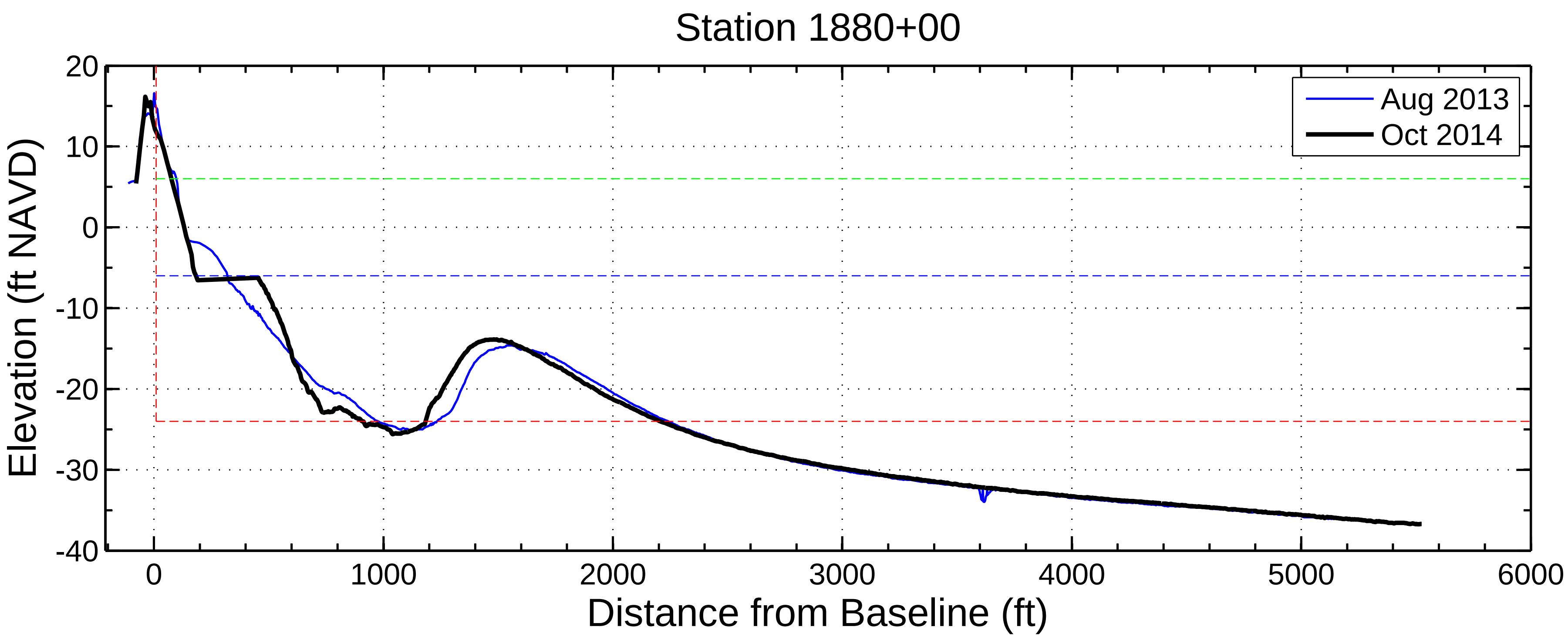
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	35.9	123.5	799.8



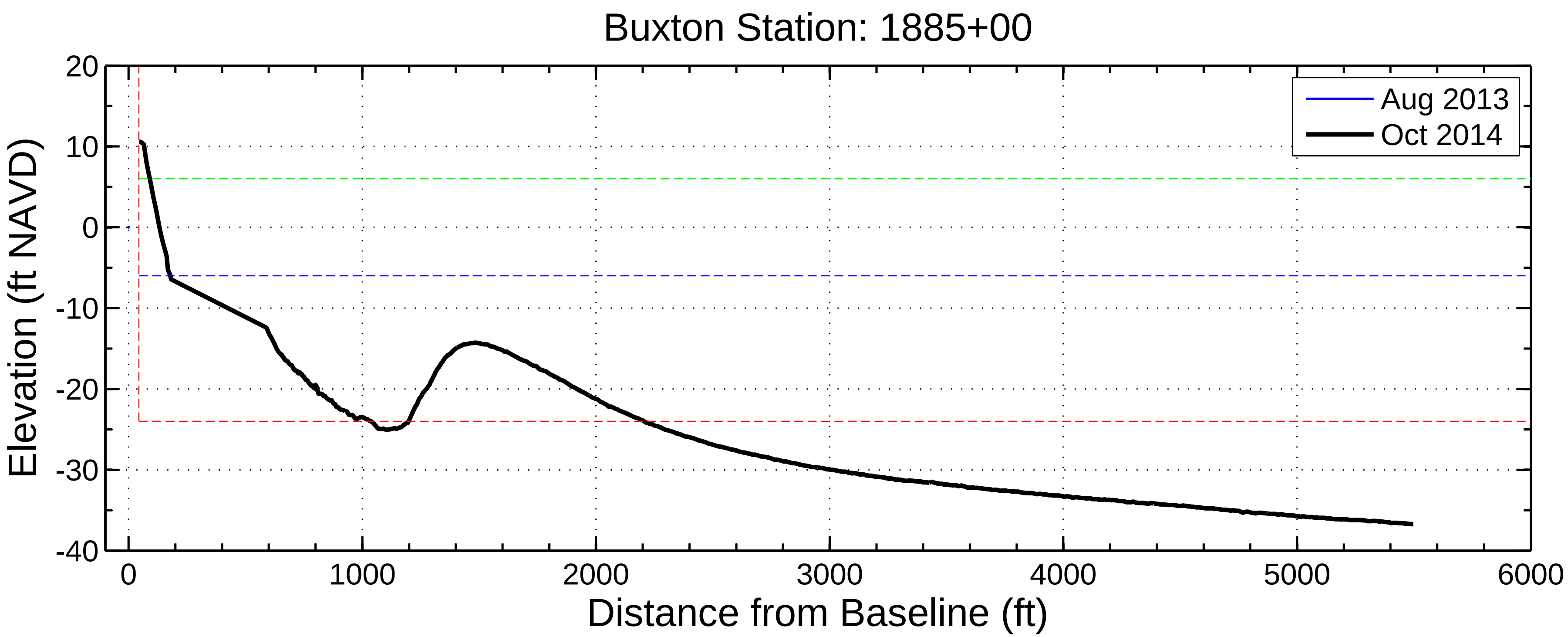
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	26.7	130.7	768.9
Oct 2014	33.2	109.6	767.0



Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	24.3	94.1	759.0

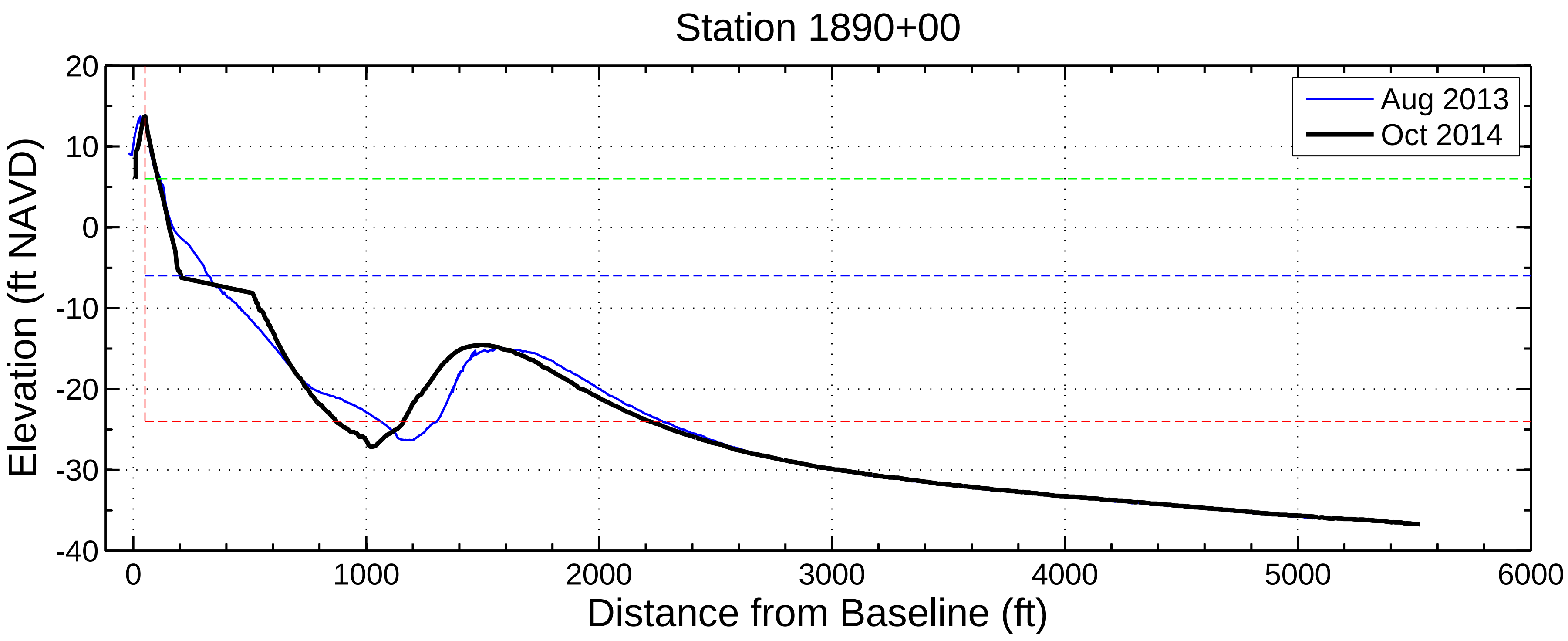


Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	10.6	82.8	673.0
Oct 2014	8.1	61.8	672.6

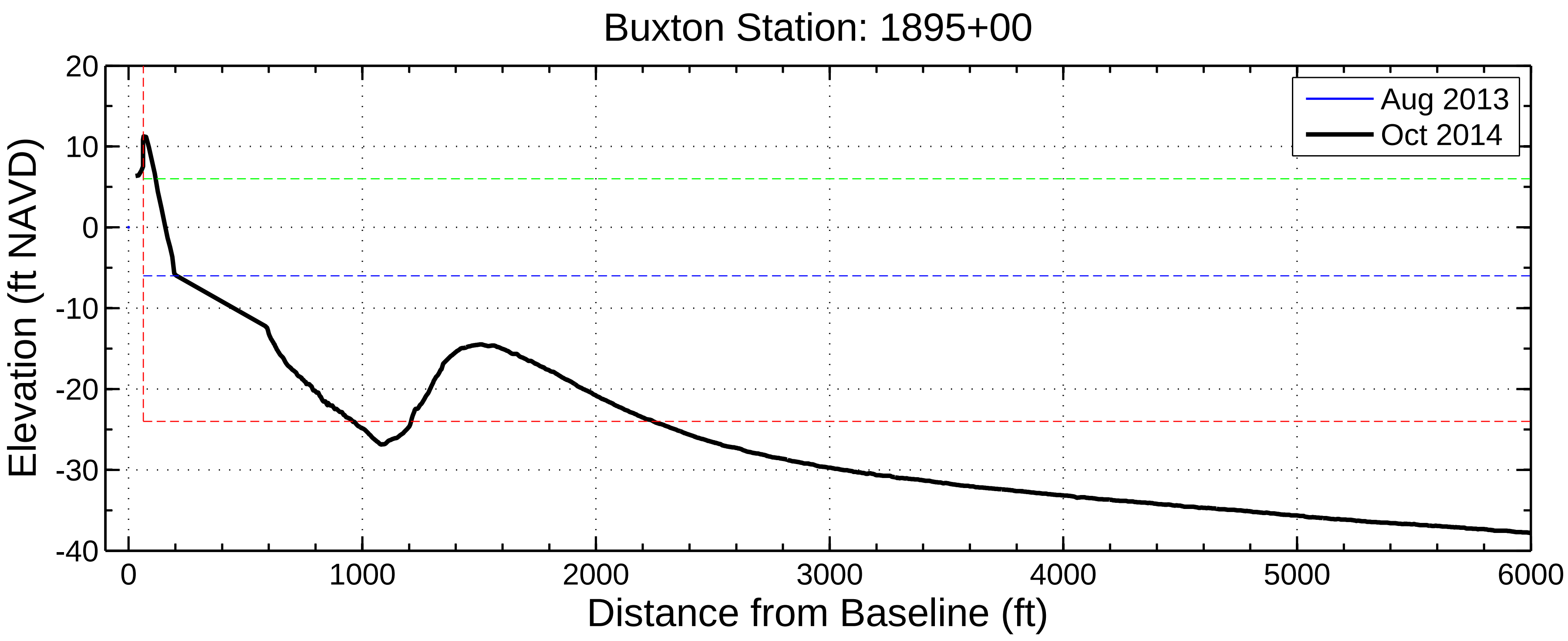


Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	5.4	45.0	631.2

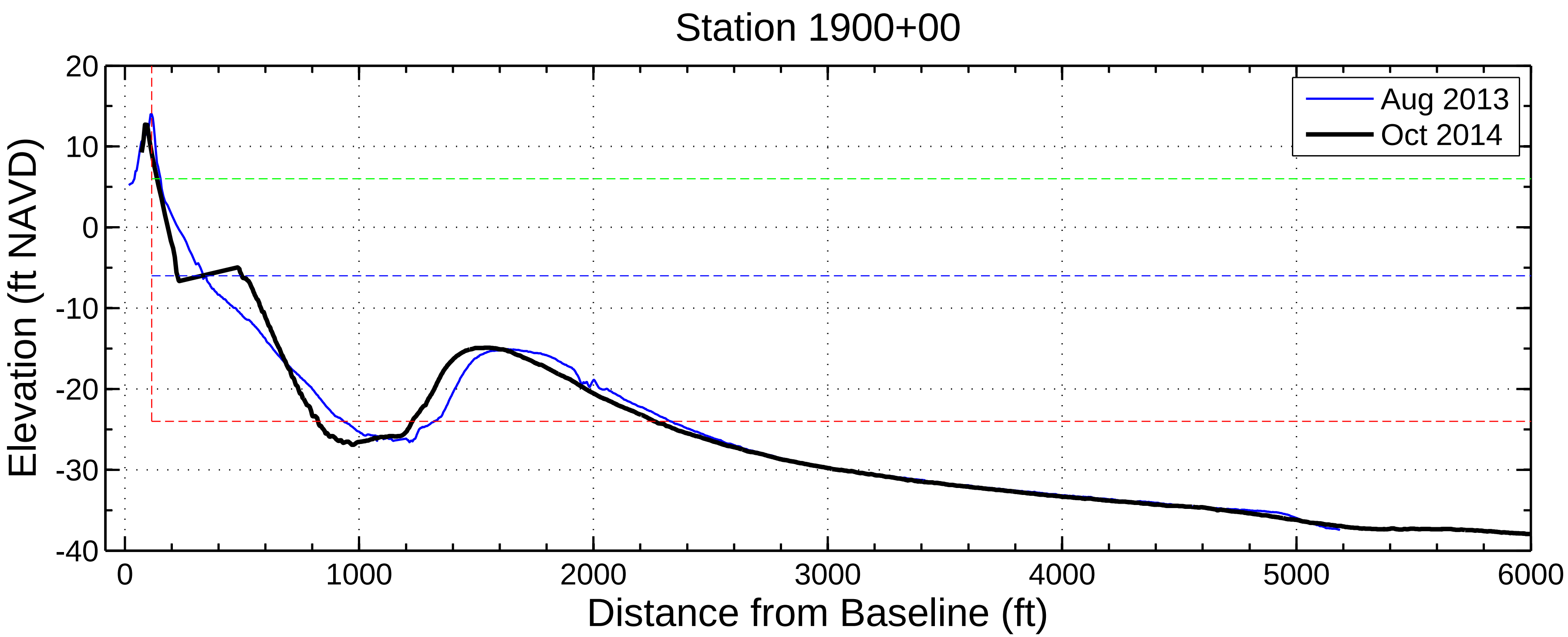
Station 1890+00



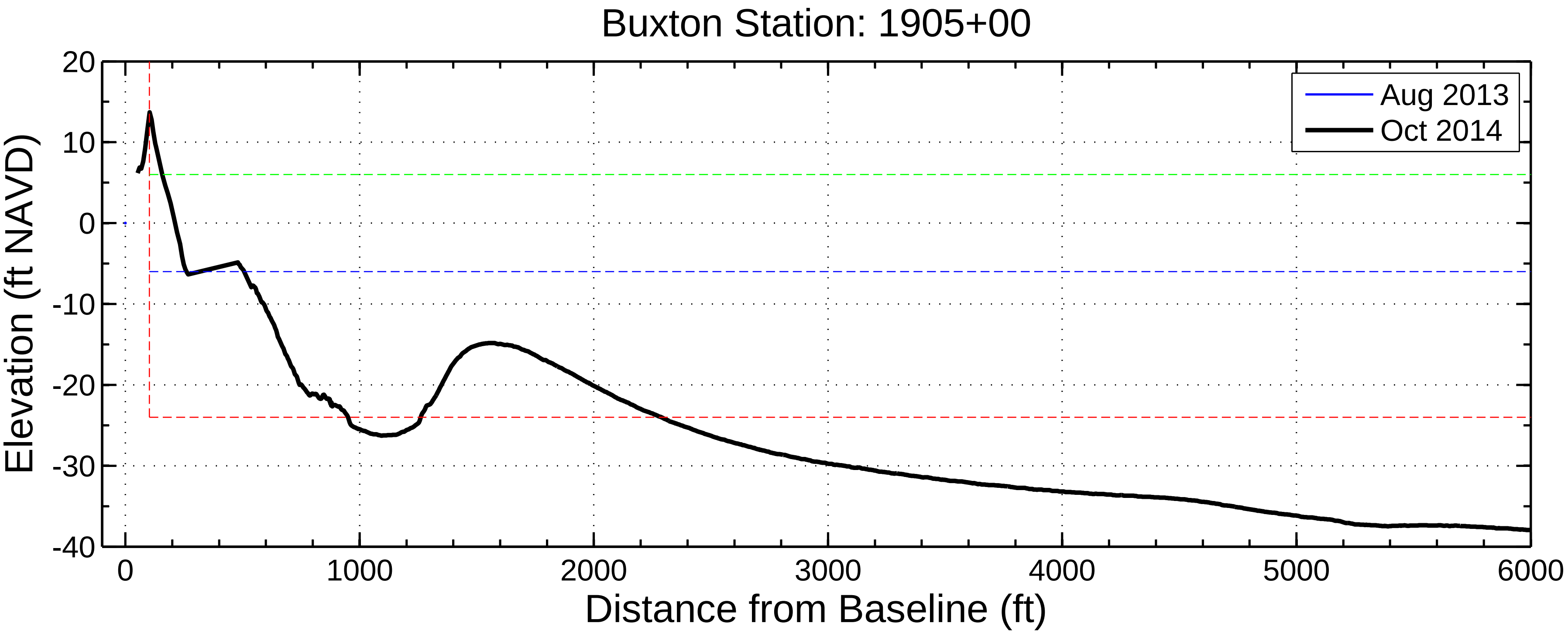
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	7.5	72.8	656.4
Oct 2014	7.7	54.5	654.7



Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	6.4	48.6	626.7

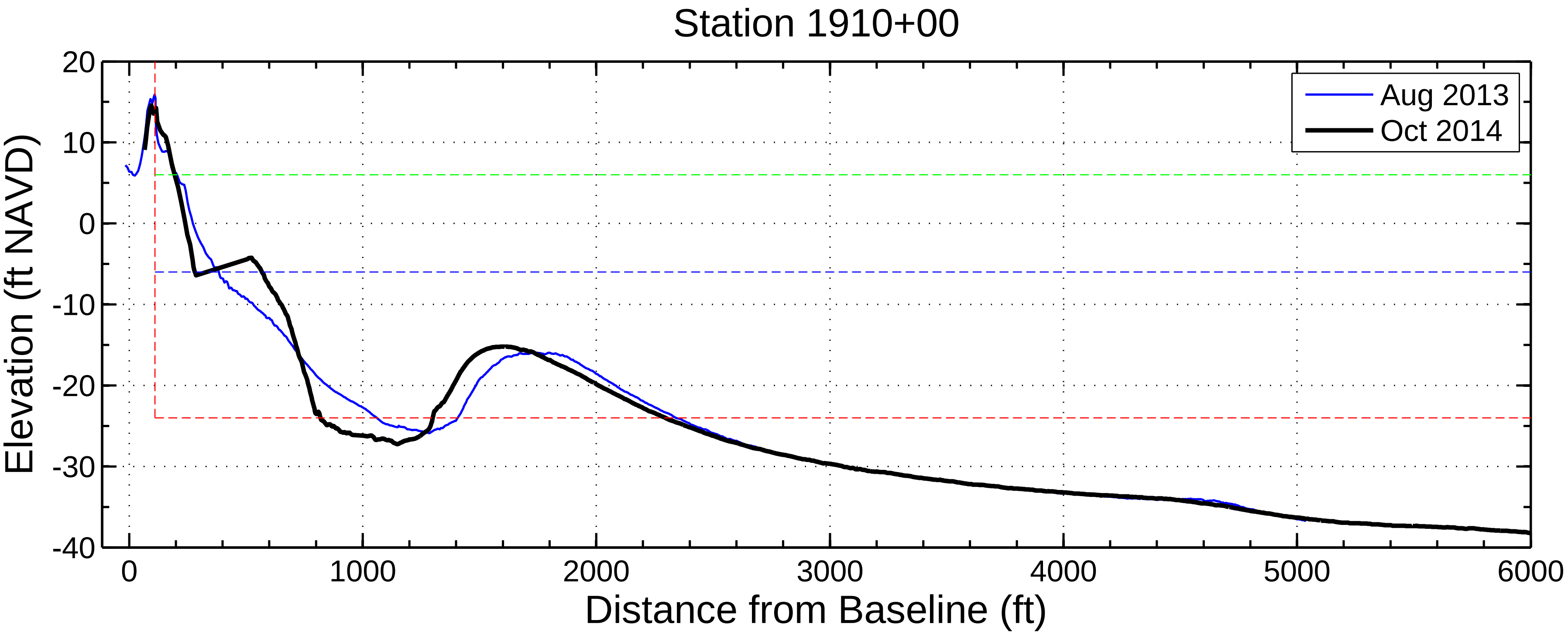


Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	5.1	56.7	598.3
Oct 2014	1.3	35.1	600.7

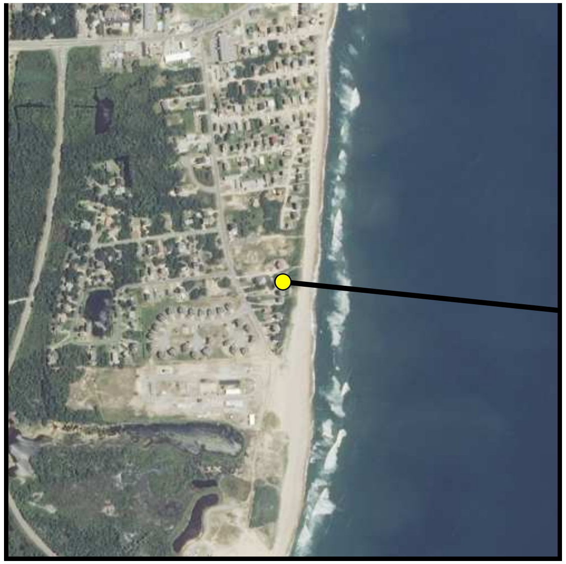


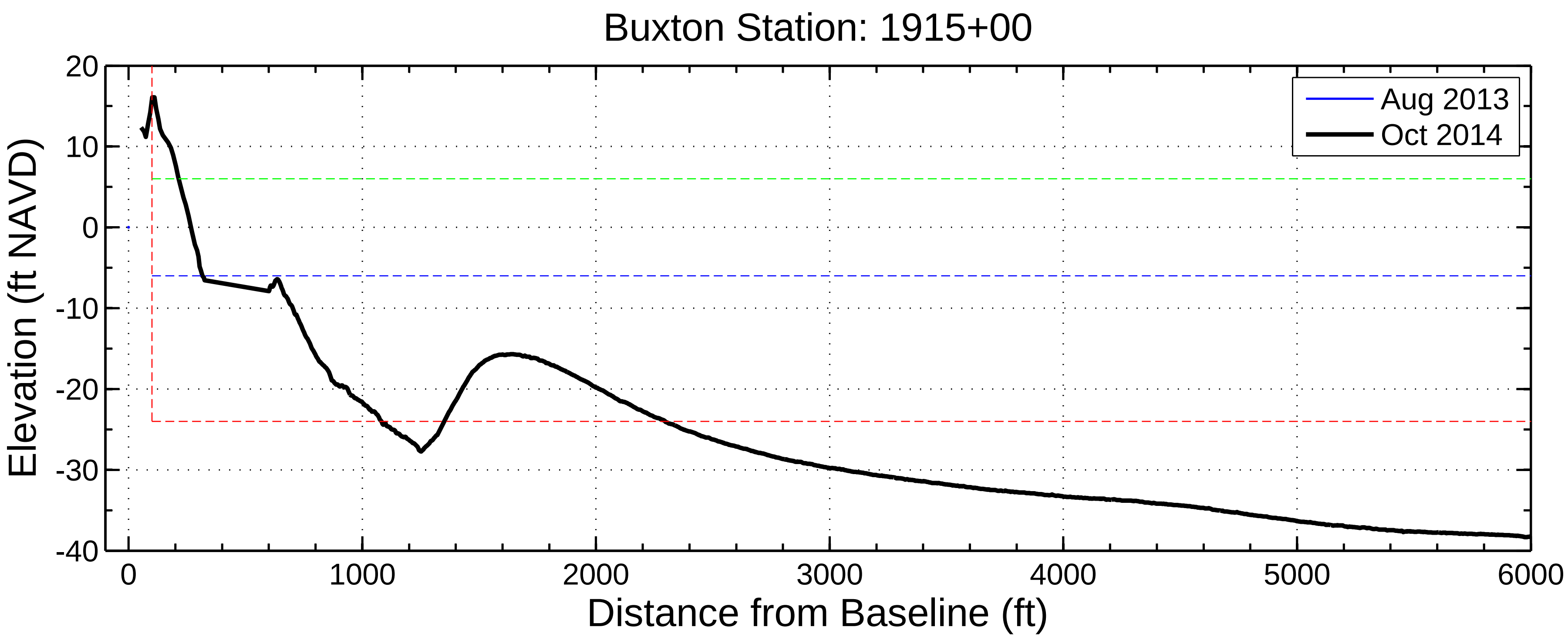
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	7.8	59.9	647.5

Station 1910+00



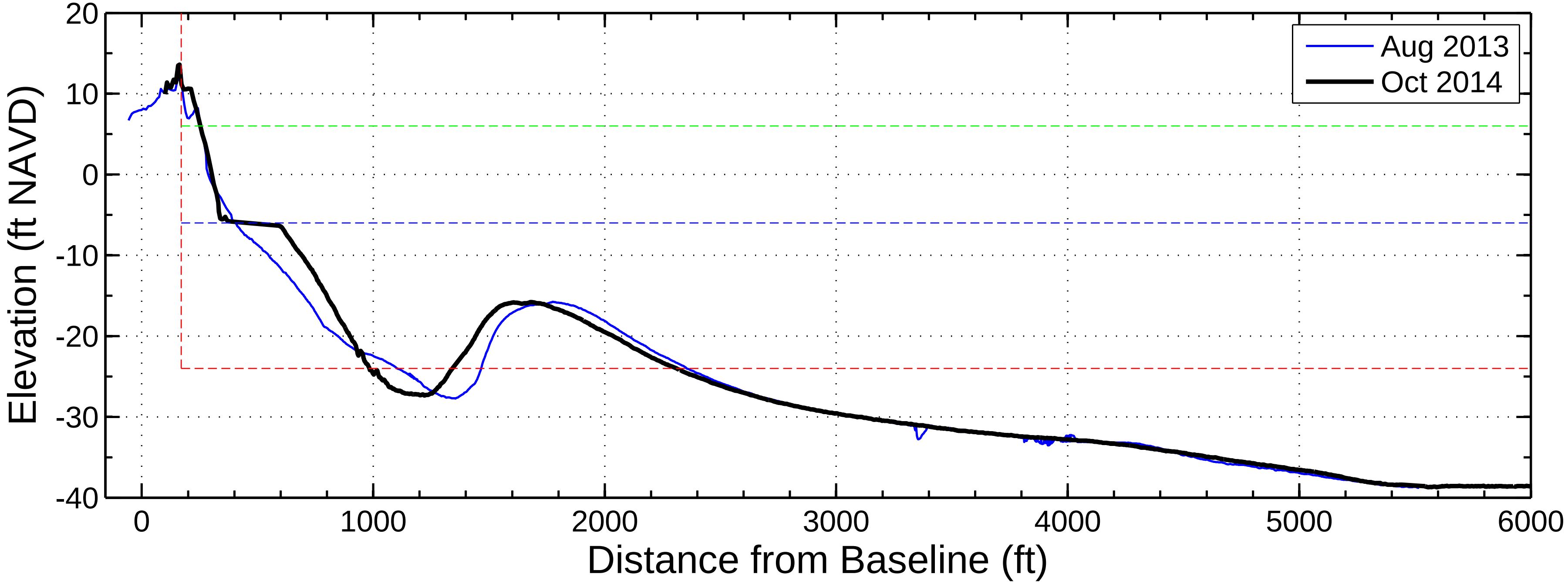
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	9.6	86.6	650.6
Oct 2014	13.6	79.5	666.8



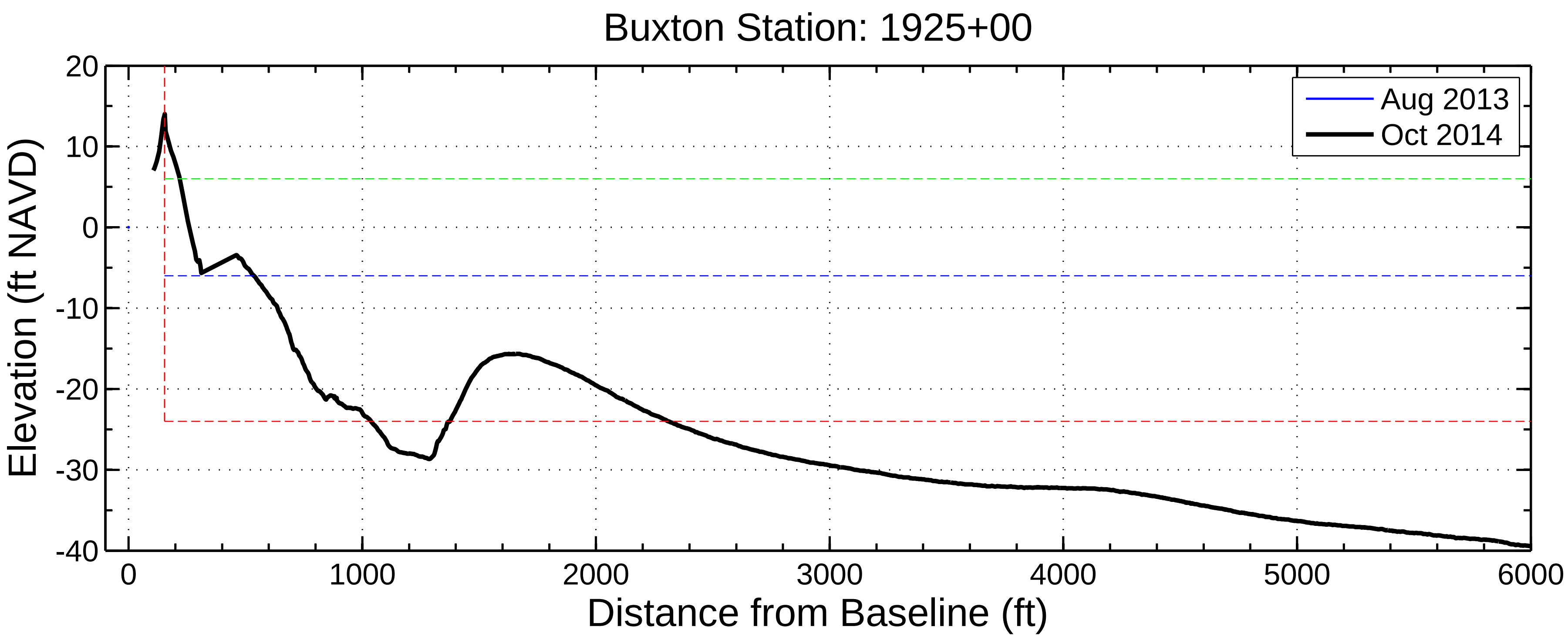


Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	22.1	96.0	730.8

Station 1920+00

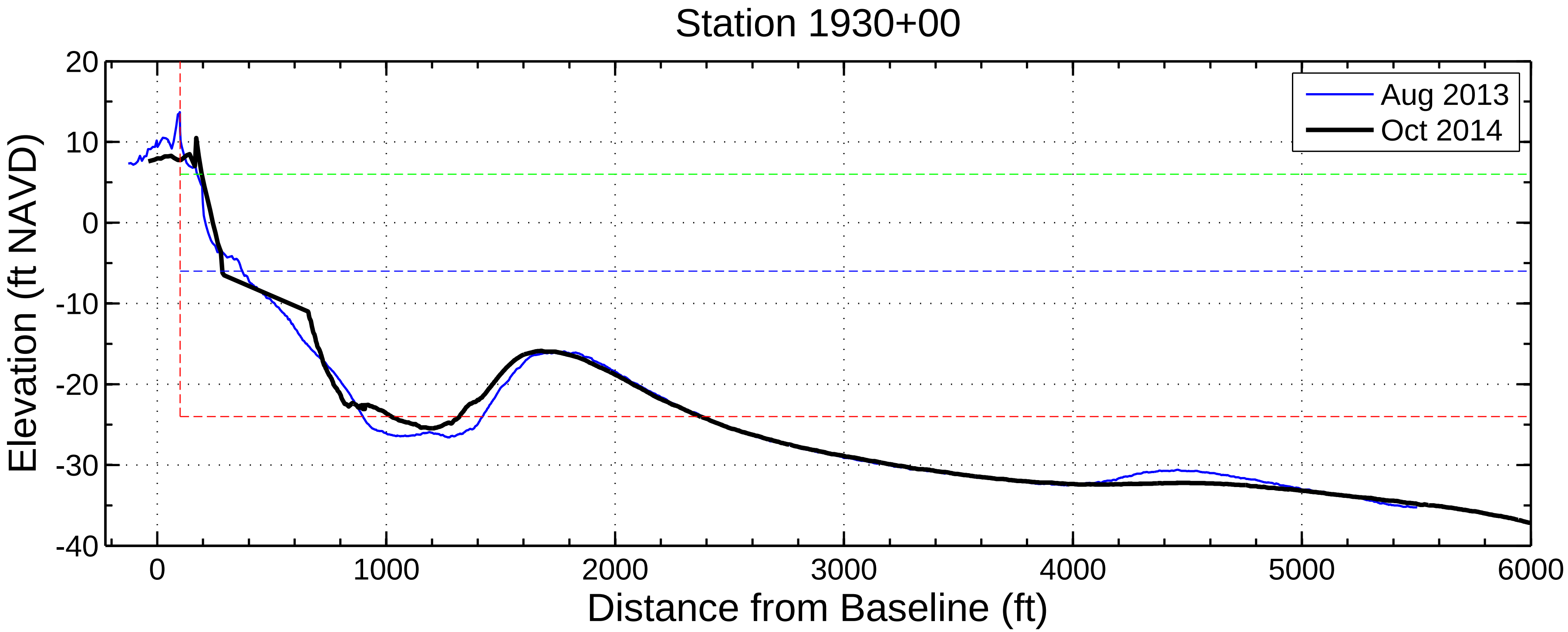


Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	6.1	67.2	593.2
Oct 2014	10.8	70.4	659.8

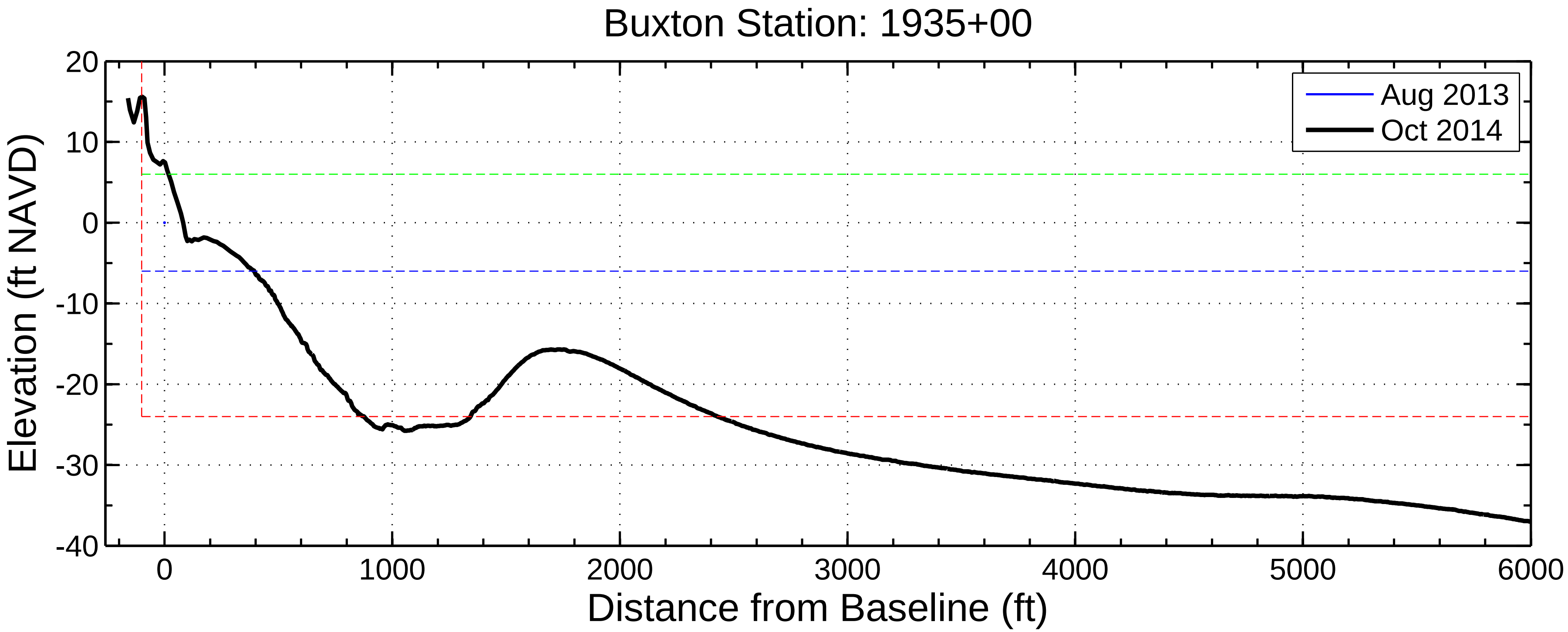


Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	7.7	67.6	627.4

Station 1930+00

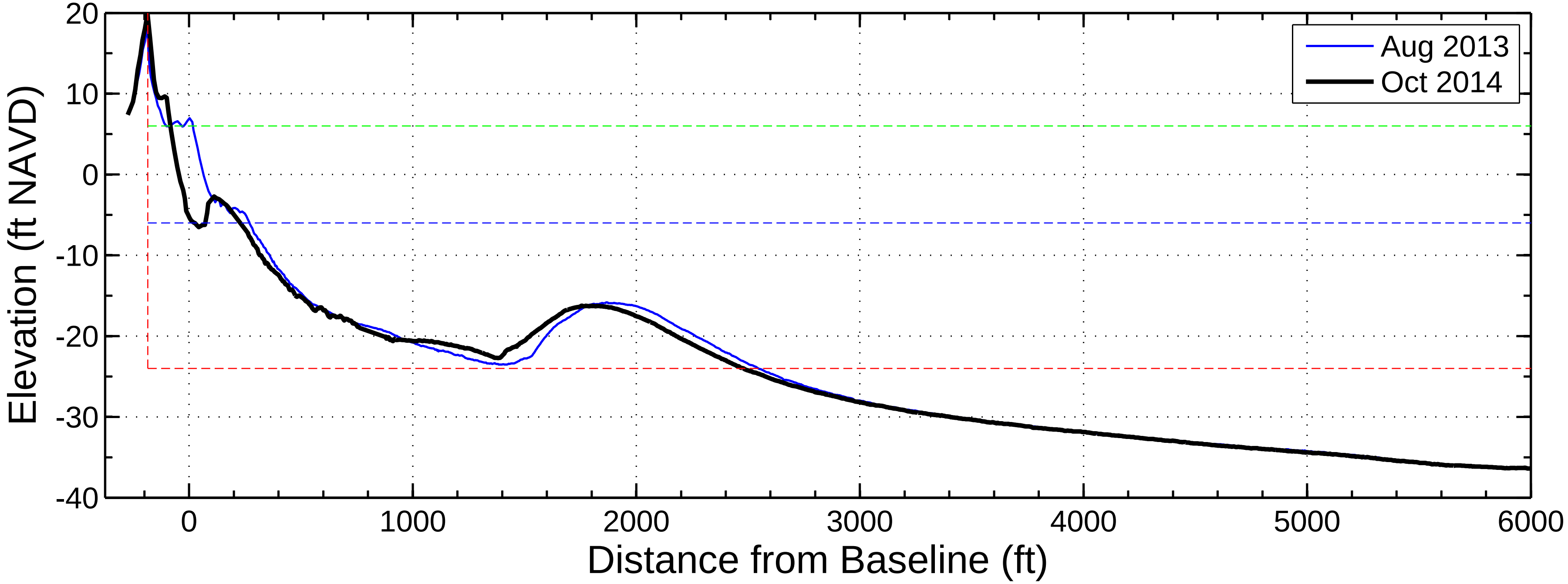


Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	4.4	64.9	603.4
Oct 2014	7.3	71.0	634.0

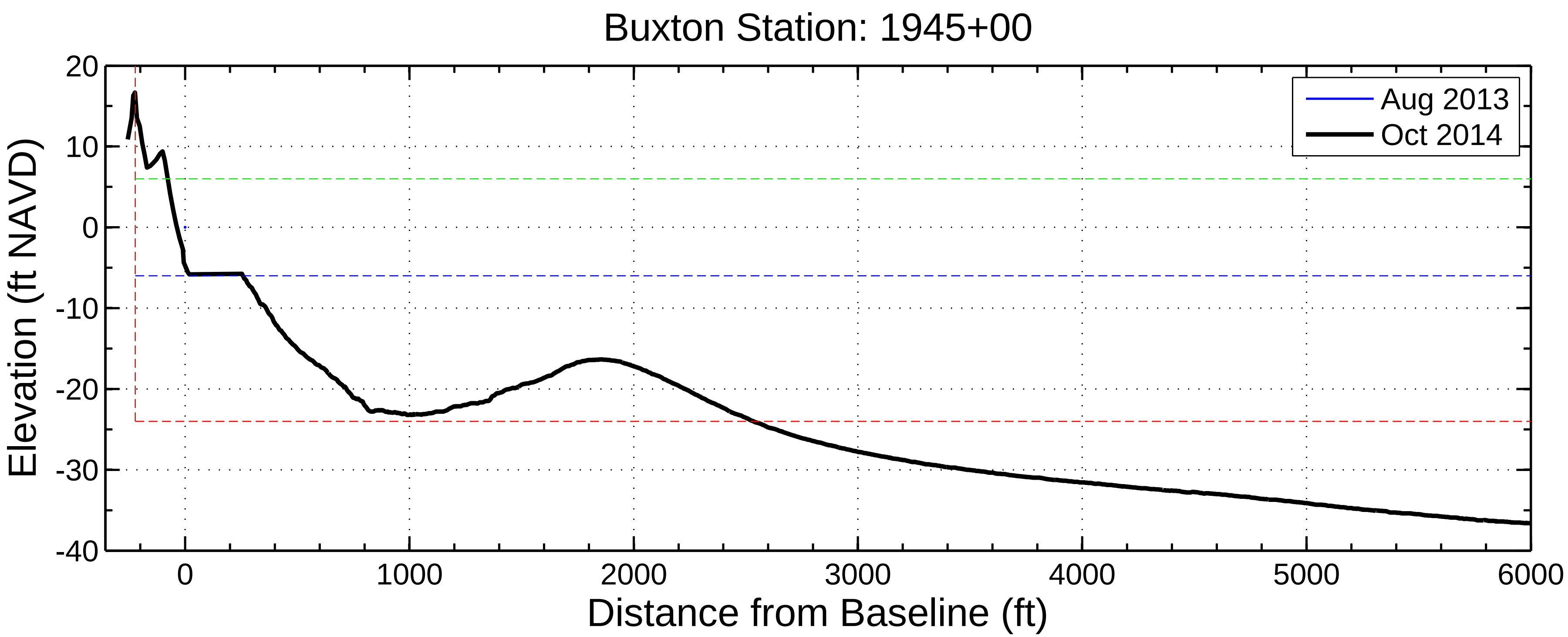


Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	13.4	121.0	796.0

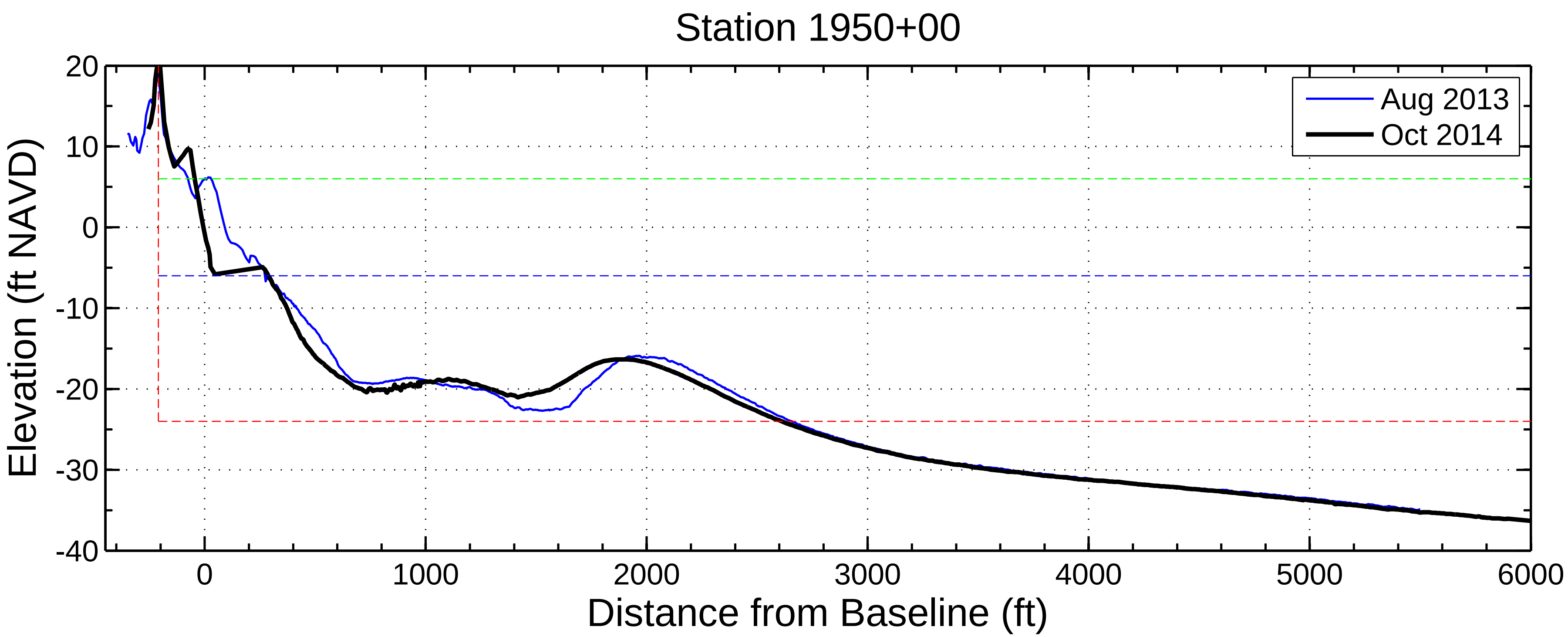
Station 1940+00



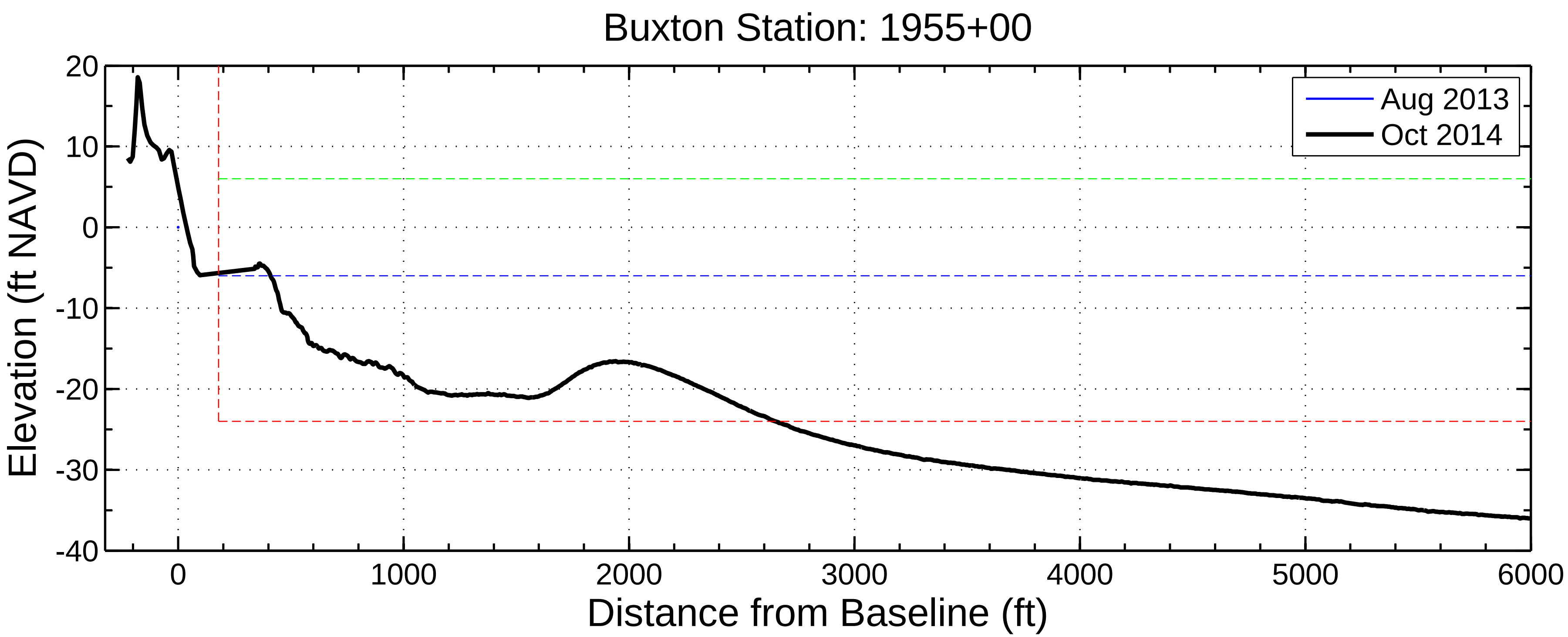
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	12.2	135.0	878.3
Oct 2014	19.1	93.9	827.0



Date	**Vol to +6**	**Vol to -6**	**Vol to -24**
Oct 2014	17.8	103.3	843.7

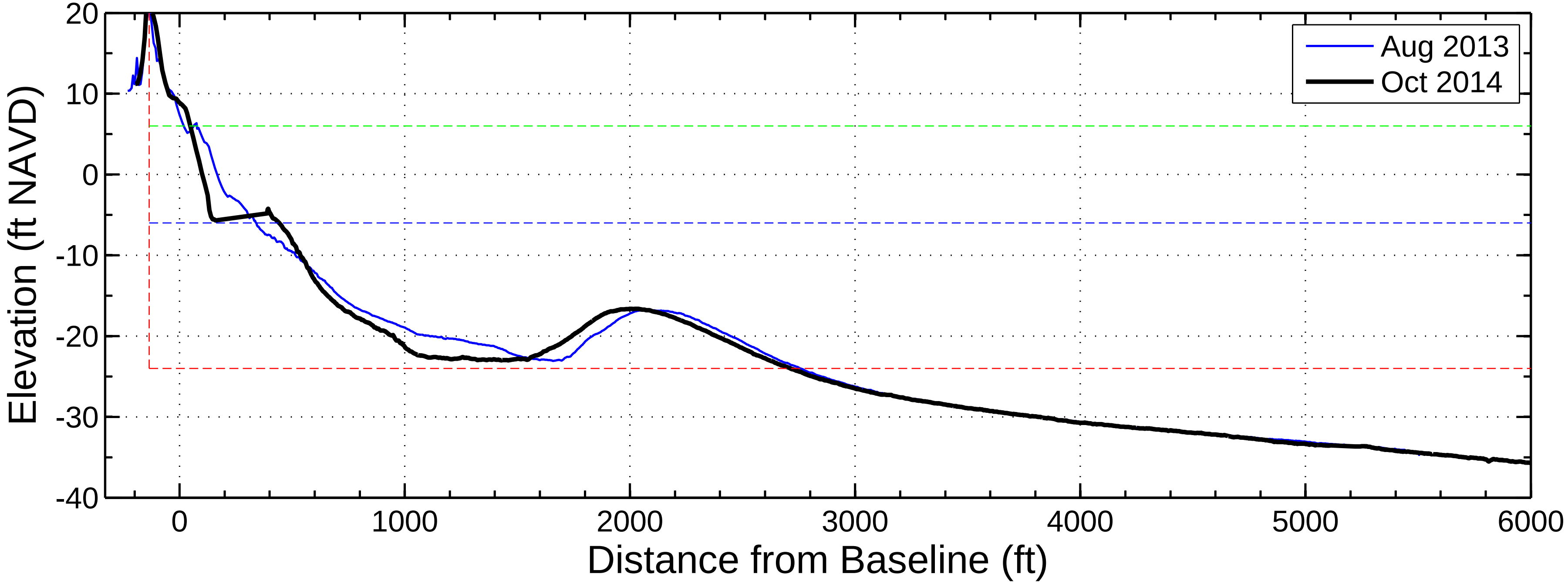


Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	18.5	162.6	975.6
Oct 2014	26.7	123.8	922.6

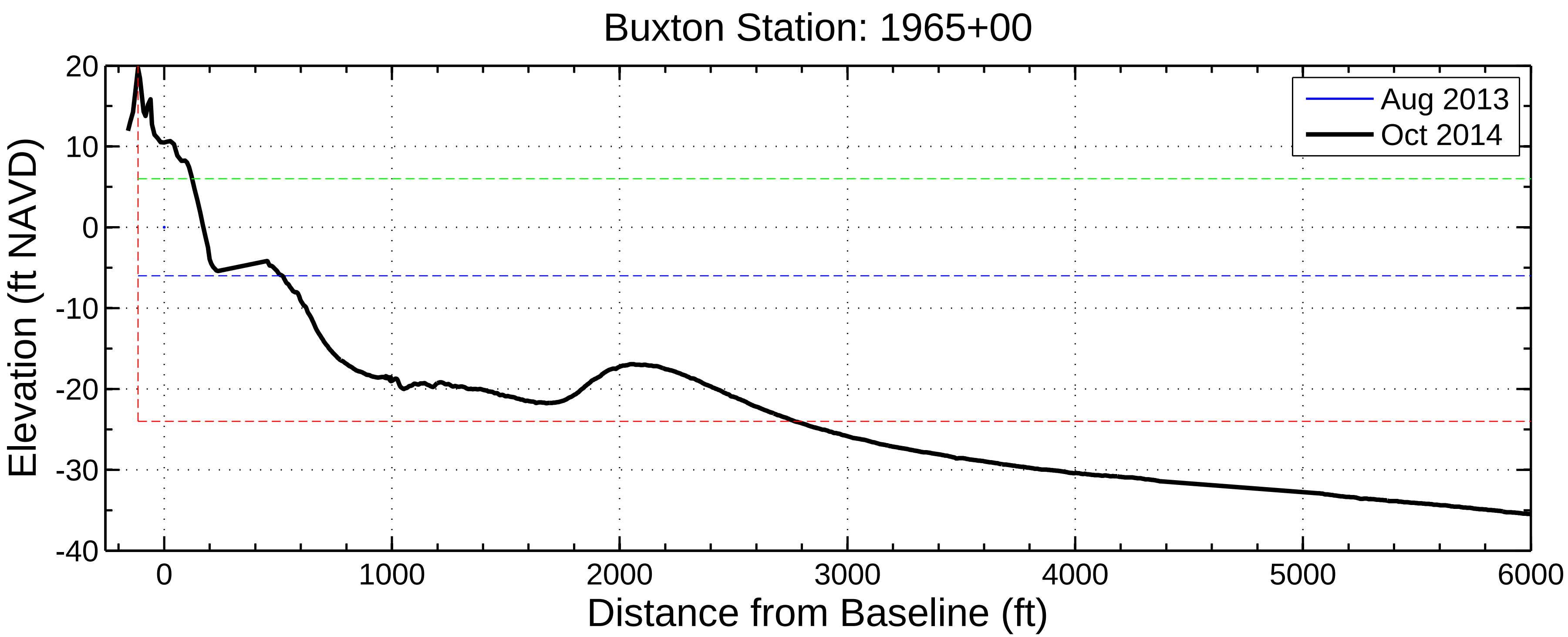


Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	0.0	6.3	623.4

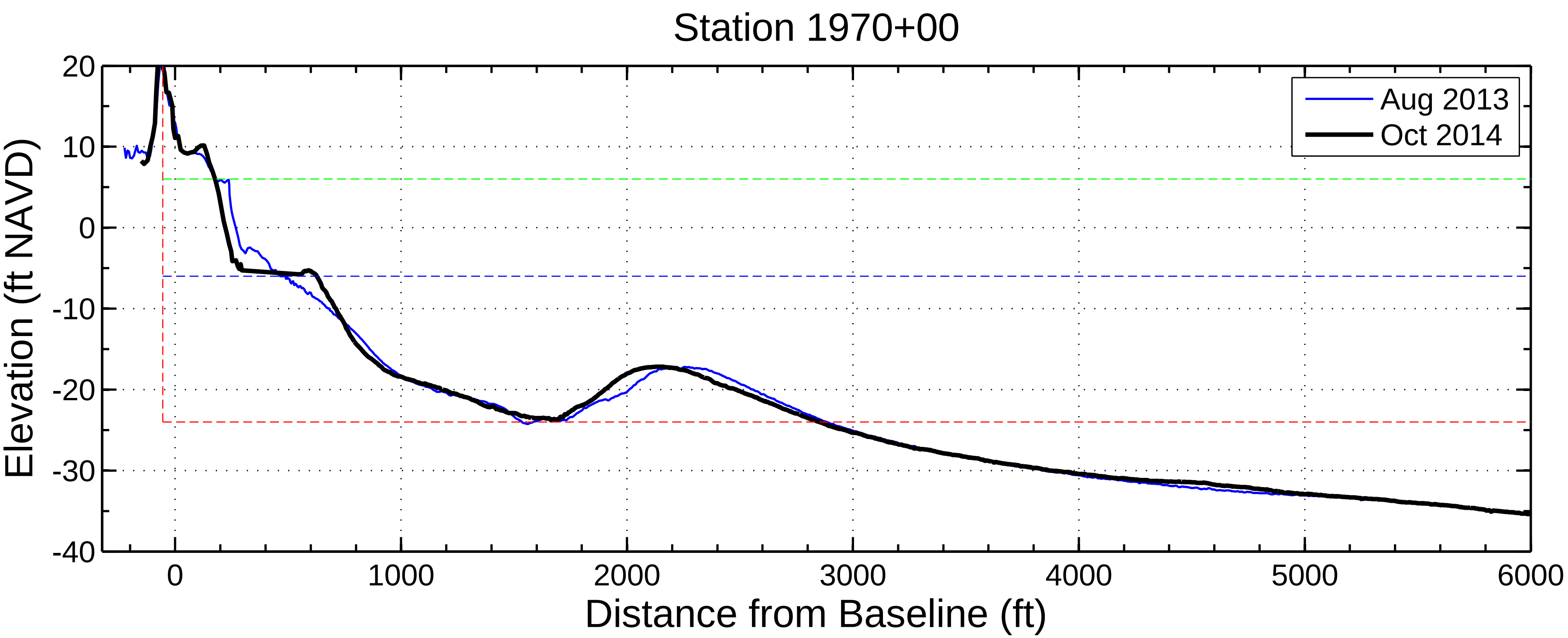
Station 1960+00



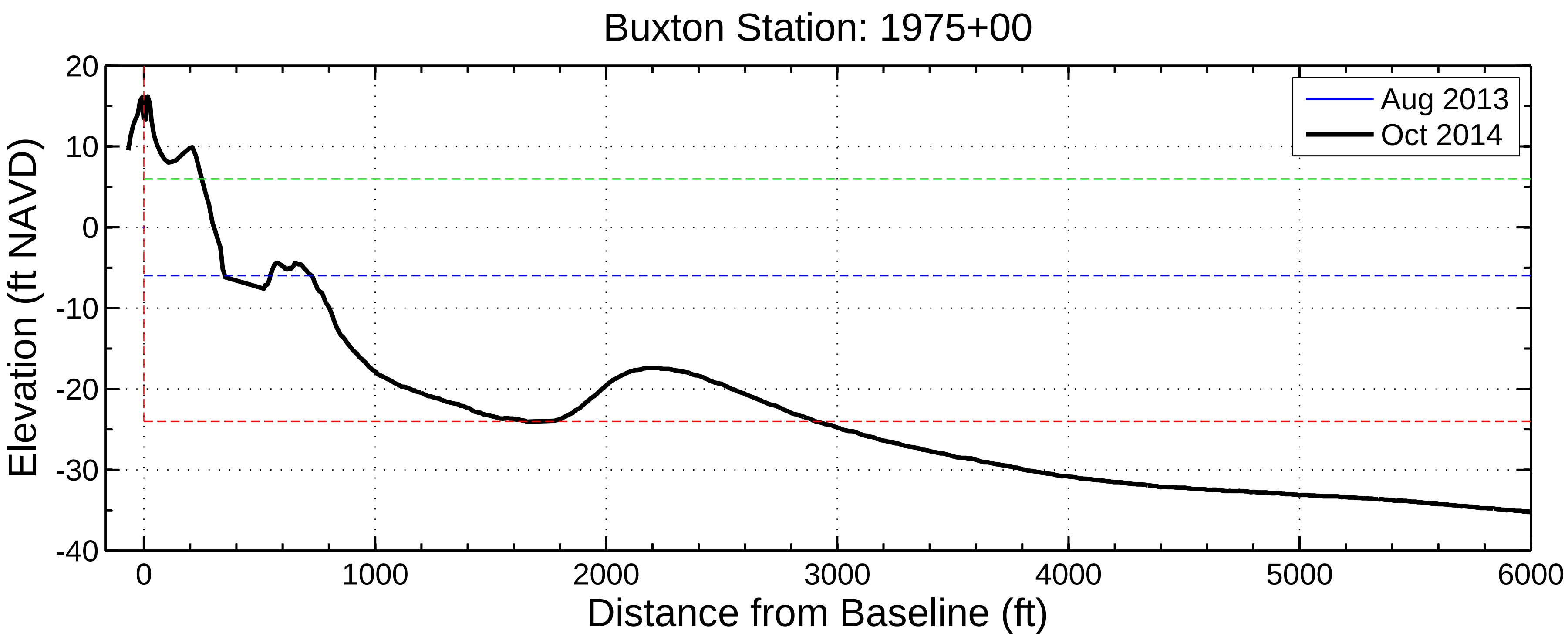
Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	33.9	175.4	992.3
Oct 2014	41.0	153.2	931.8



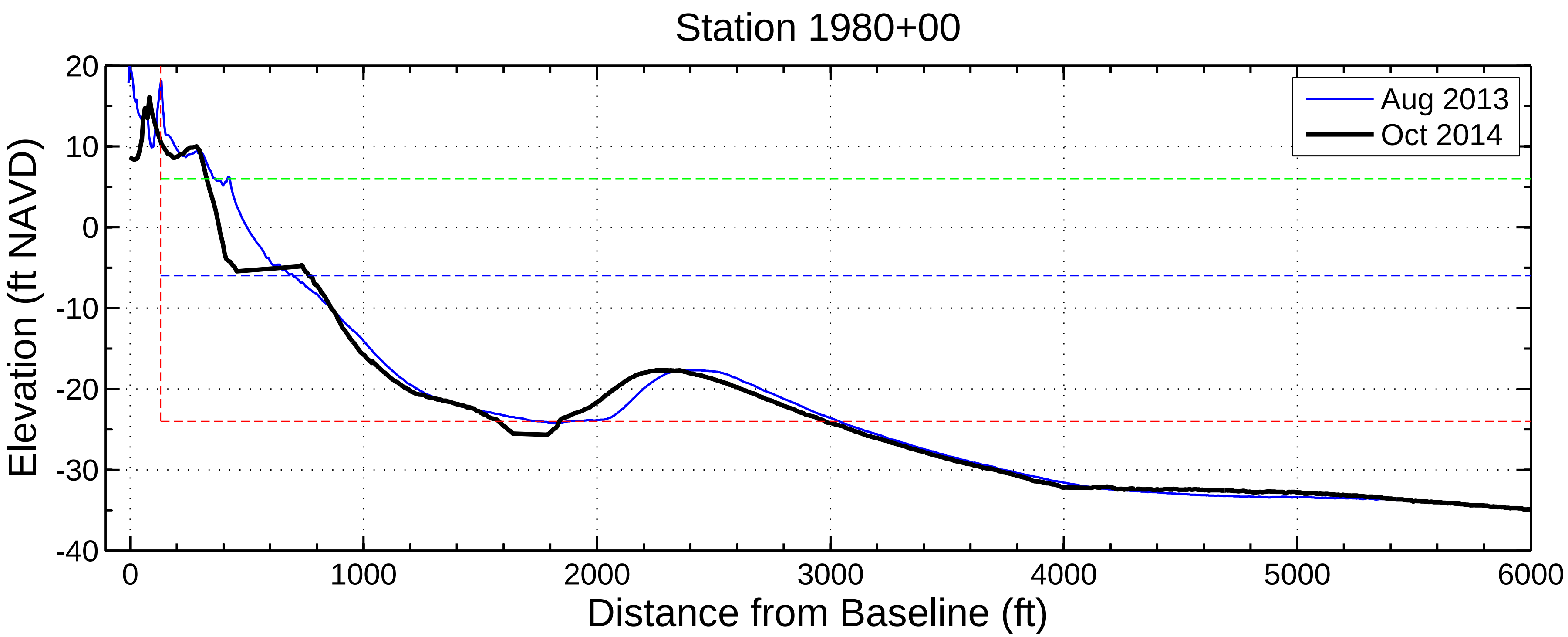
Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	46.1	185.9	1044.3



Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	40.2	197.2	1015.7
Oct 2014	42.2	173.5	1001.9



Date	Vol to +6	Vol to -6	Vol to -24
Oct 2014	34.9	176.6	983.8



Date	Vol to +6	Vol to -6	Vol to -24
Aug 2013	31.3	202.8	966.9
Oct 2014	23.1	145.7	908.1

ATTACHMENT 3

Tabulated Unit Volumes by Contour Interval

ATTACHMENT 3. Unit volumes by contour interval.

Station	Distance to Next	August 2013 – Unit Volume (cy/ft)				October 2014 – Unit Volume (cy/ft)			
		Vol to +10	Vol to -2	Vol to -12	Vol to -24	Vol to +10	Vol to -2	Vol to -12	Vol to -24
1720+00	500	ND	ND	ND	ND	32.47	110.9	288.4	960.0
1725+00	500	ND	ND	ND	ND	26.83	110.1	302.0	976.0
1730+00	500	ND	ND	ND	ND	17.75	95.6	277.2	952.2
1735+00	500	ND	ND	ND	ND	15.95	124.4	353.7	1054.2
1740+00	500	ND	ND	ND	ND	12.23	115.7	357.8	1052.4
1745+00	500	ND	ND	ND	ND	15.52	82.4	253.4	938.6
1750+00	500	ND	ND	ND	ND	15.64	58.2	161.4	846.7
1755+00	500	ND	ND	ND	ND	8.78	54.2	195.5	879.2
1760+00	500	ND	ND	ND	ND	16.29	80.3	210.8	897.9
1765+00	500	ND	ND	ND	ND	21.46	118.5	282.7	990.9
1770+00	500	ND	ND	ND	ND	40.92	149.9	324.4	1058.4
1775+00	500	ND	ND	ND	ND	22.39	123.8	303.5	1017.0
1780+00	500	ND	ND	ND	ND	12.11	107.5	294.5	1003.3
1785+00	500	ND	ND	ND	ND	16.40	100.3	257.7	956.5
1790+00	500	10.0	75.3	230.0	838.3	9.38	82.0	241.8	894.4
1795+00	500					16.55	107.5	264.6	891.3
1800+00	500	12.1	86.3	250.7	862.1	11.04	97.6	246.5	909.4
1805+00	500					10.51	88.2	232.1	841.1
1810+00	500	3.7	91.5	254.6	910.8	8.01	107.8	260.4	918.9
1815+00	500					13.55	114.6	280.5	914.1
1820+00	500	21.9	103.3	278.4	885.8	17.51	106.4	257.2	880.2
1825+00	500					17.30	93.2	236.5	779.1
1830+00	500	20.1	114.0	287.8	909.4	23.21	105.4	257.1	904.1
1835+00	500					34.72	136.1	298.8	905.9
1840+00	500	16.3	72.8	225.2	770.2	21.51	89.3	203.8	797.3
1845+00	500					27.70	108.2	280.1	841.7
1850+00	500	11.3	76.3	228.2	744.9	13.51	70.9	208.9	722.5
1855+00	500					7.05	44.0	164.8	718.4
1860+00	500	14.2	84.9	240.2	771.8	8.82	72.1	211.0	774.4
1865+00	500					18.76	89.5	246.1	799.8
1870+00	500	11.5	84.3	233.5	768.9	18.27	79.1	222.2	767.0
1875+00	500					11.03	65.8	209.0	759.0
1880+00	500	2.7	43.3	169.4	673.0	1.06	38.7	168.1	672.6
1885+00	500					0.37	27.4	114.6	631.2
1890+00	500	1.8	38.6	155.3	656.4	1.69	34.3	148.6	654.7
1895+00	500					0.77	30.1	120.9	626.7
1900+00	500	1.4	29.4	127.1	598.3	0.00	17.1	133.8	600.7
1905+00	500					1.90	35.1	162.8	647.5
1910+00	500	1.2	52.7	170.3	650.7	3.41	48.1	194.2	666.8
1915+00	500					7.63	66.5	211.7	730.8
1920+00	500	0.3	38.7	142.3	593.2	1.08	45.5	179.4	659.8
1925+00	500					1.16	34.9	168.9	627.4
1930+00	500	0.1	34.8	147.4	603.4	0.03	44.9	157.8	634.0
1935+00	500					3.89	61.1	248.1	796.0
1940+00	500	2.7	81.3	250.6	878.3	6.22	56.6	201.1	827.0
1945+00	500					3.44	68.8	226.5	843.7
1950+00	500	5.4	99.3	293.3	975.6	8.66	83.4	248.2	922.6
1955+00	500					8.05	89.0	274.1	988.7
1960+00	500	14.7	114.7	309.0	992.3	18.61	105.6	297.7	931.8
1965+00	500					16.11	126.4	343.7	1044.3
1970+00	500	13.8	131.5	349.1	1015.6	13.26	120.1	338.7	1001.9
1975+00	500					7.07	119.7	343.5	983.8
1980+00	0	5.5	132.3	356.2	966.7	0.12	92.6	303.5	908.1

ATTACHMENT 4

Tabulated Historical Shorelines

(distances from baseline in feet)

ATTACHMENT 4. Historical shorelines (distance from baseline in feet).

CSE Station	1925-46	1970-88	1998	2004	2009
1744+87	517	300	328	257	301
1777+68	604	294	214	251	242
1790+63	735	332	277	250	189
1800+63	719	377	252	238	134
1810+63	794	369	225	242	100
1821+84	803	414	271	215	138
1830+63	809	371	266	218	104
1840+63	719	384	186	119	95
1850+63	716	358	197	173	101
1860+63	717	398	217	198	101
1870+63	680	365	233	196	163
1880+63	650	300	210	187	166
1890+63	627	368	259	227	170
1900+63	581	439	277	274	180
1901+75	576	443	285	266	198
1910+63	560	396	353	201	228
1920+63	516	456	383	282	259
1928+11	490	358	324	241	218
1940+63	629	243	43	152	−37
1950+63	723	122	−89	80	−13
1960+63	827	93	6	64	112
1970+63	893	272	61	159	250
1983+77	1,012	630	265	361	351

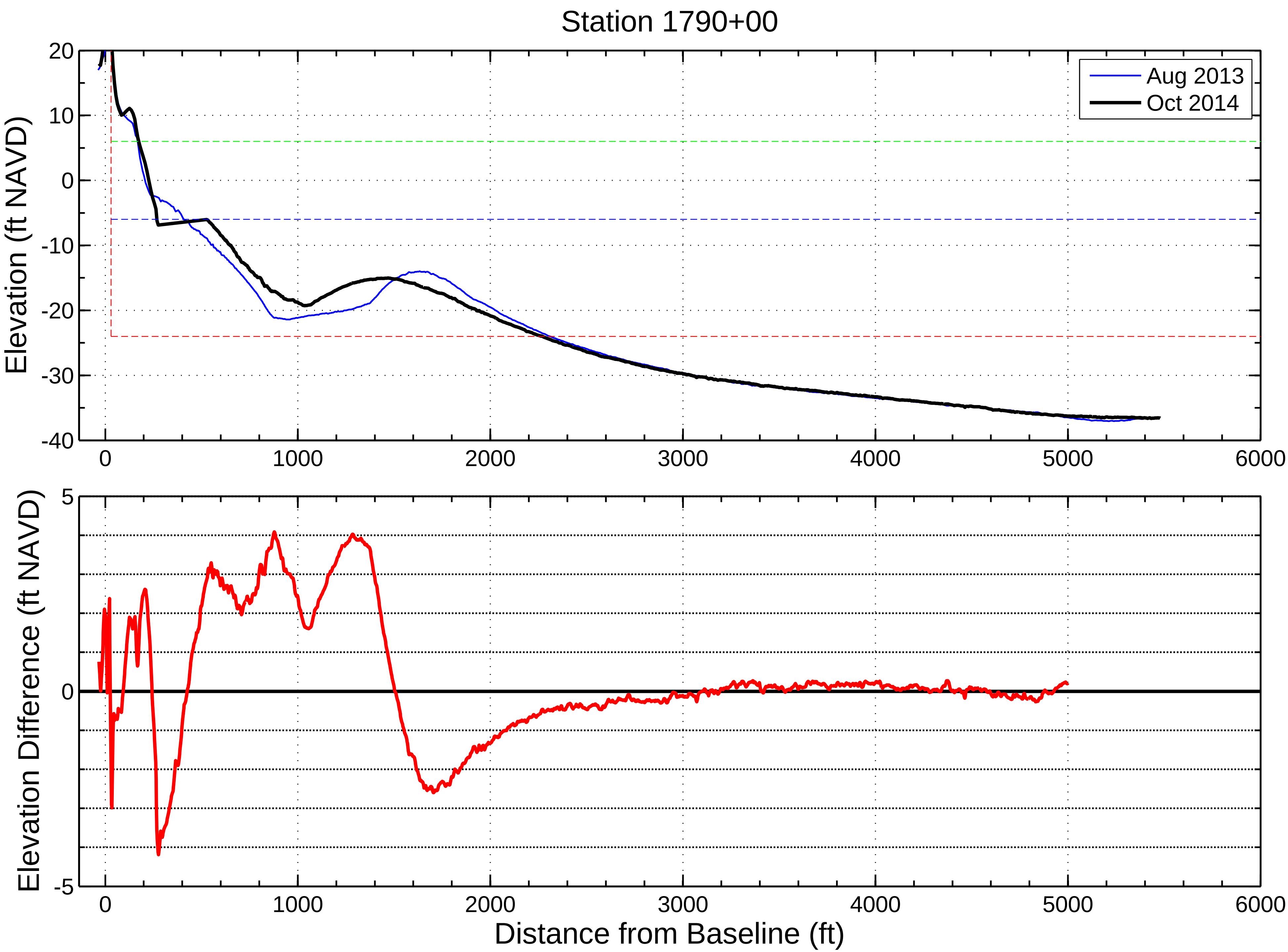
ATTACHMENT 5

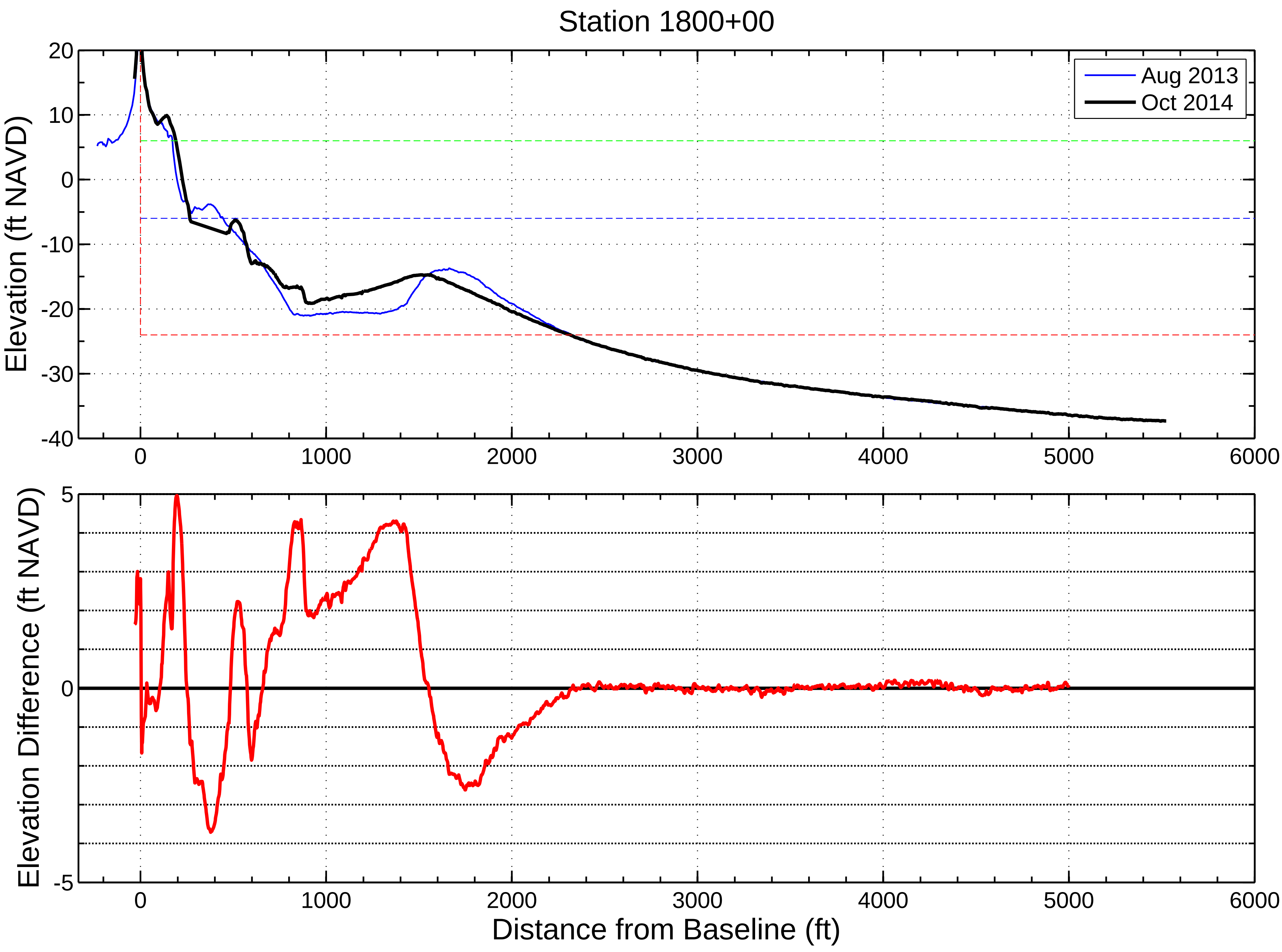
Depth of Closure (DOC) Analysis

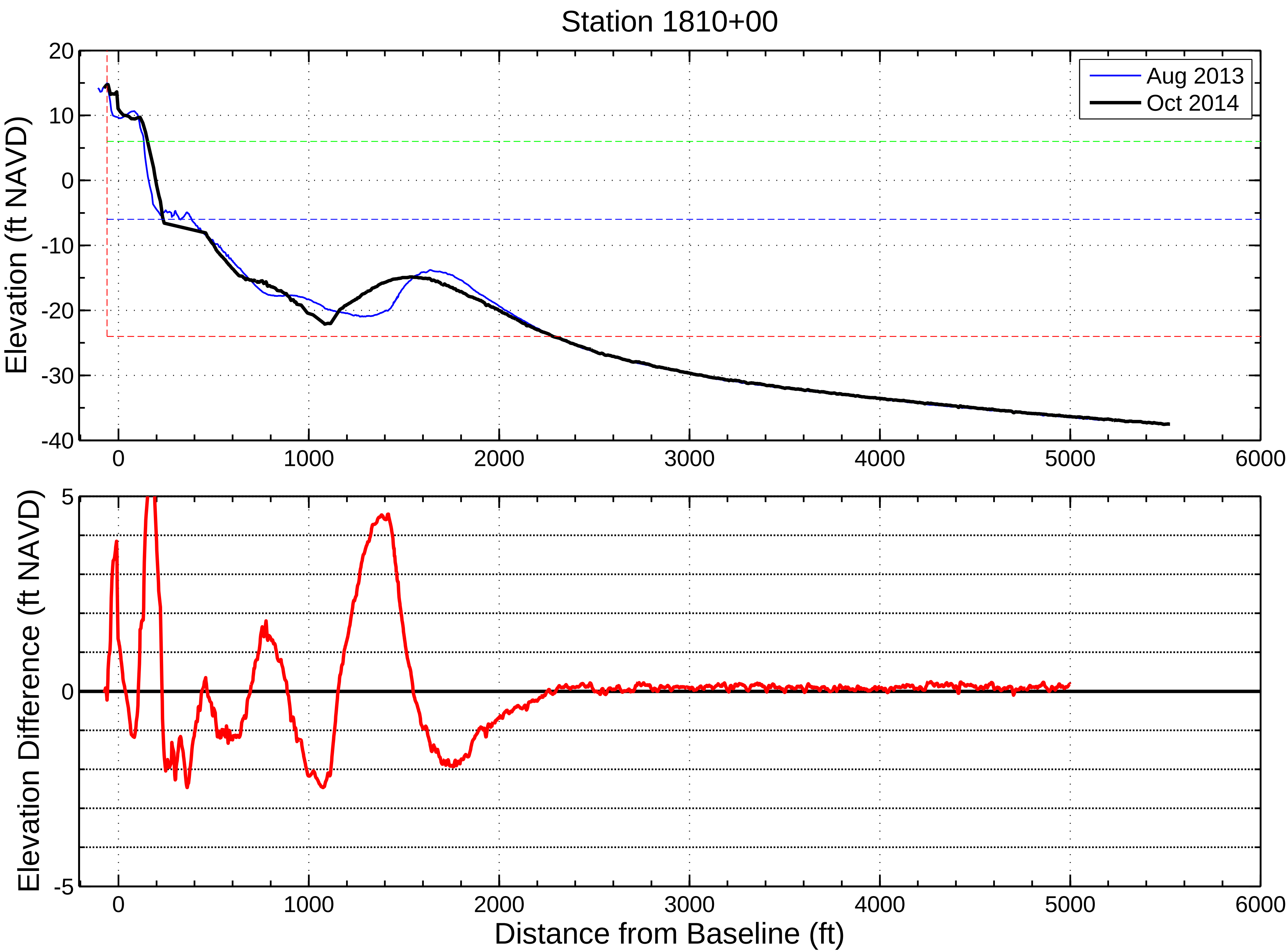
ATTACHMENT 5

Depth of Closure (DOC) Analysis

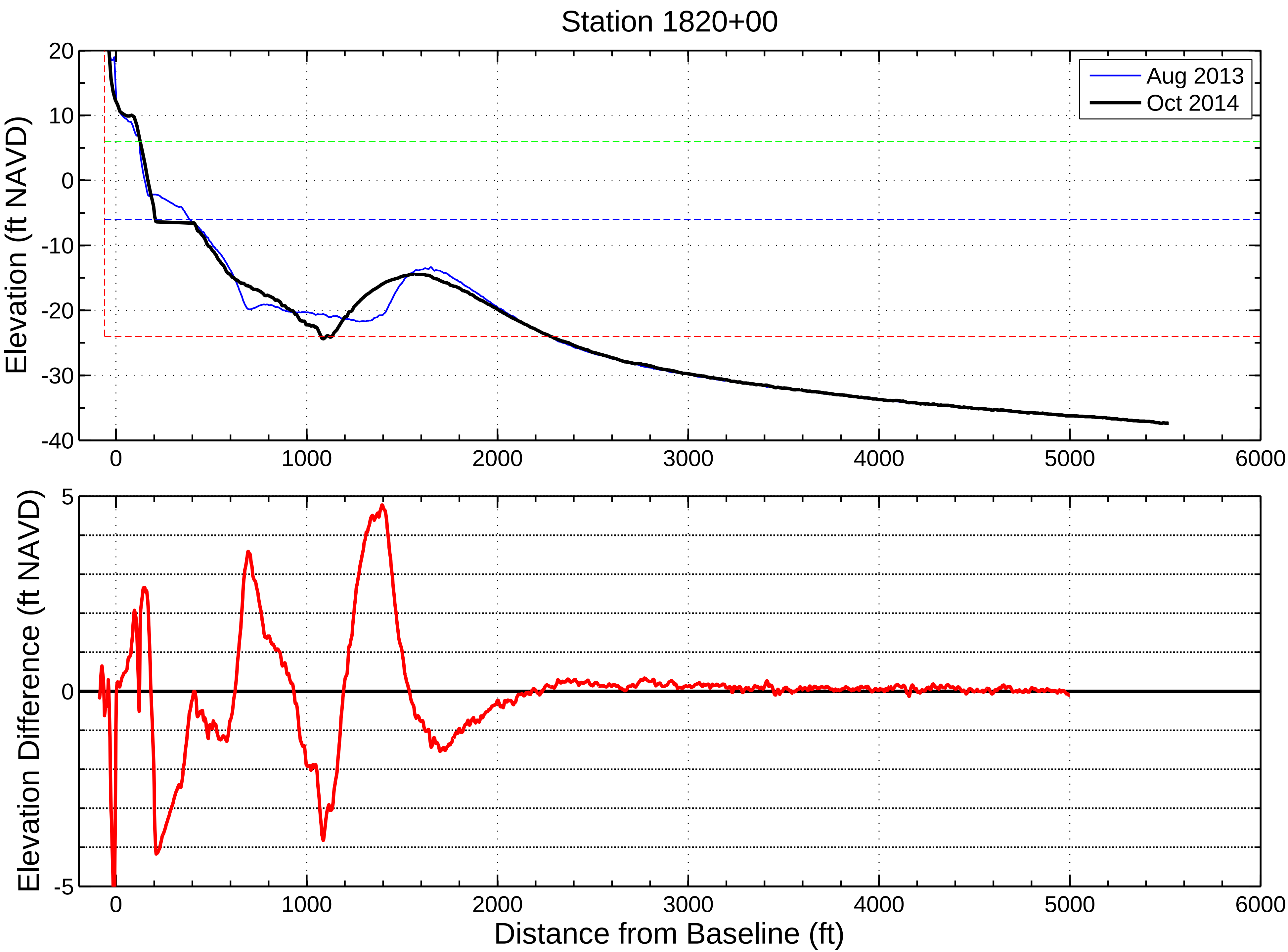
Station 1790+00



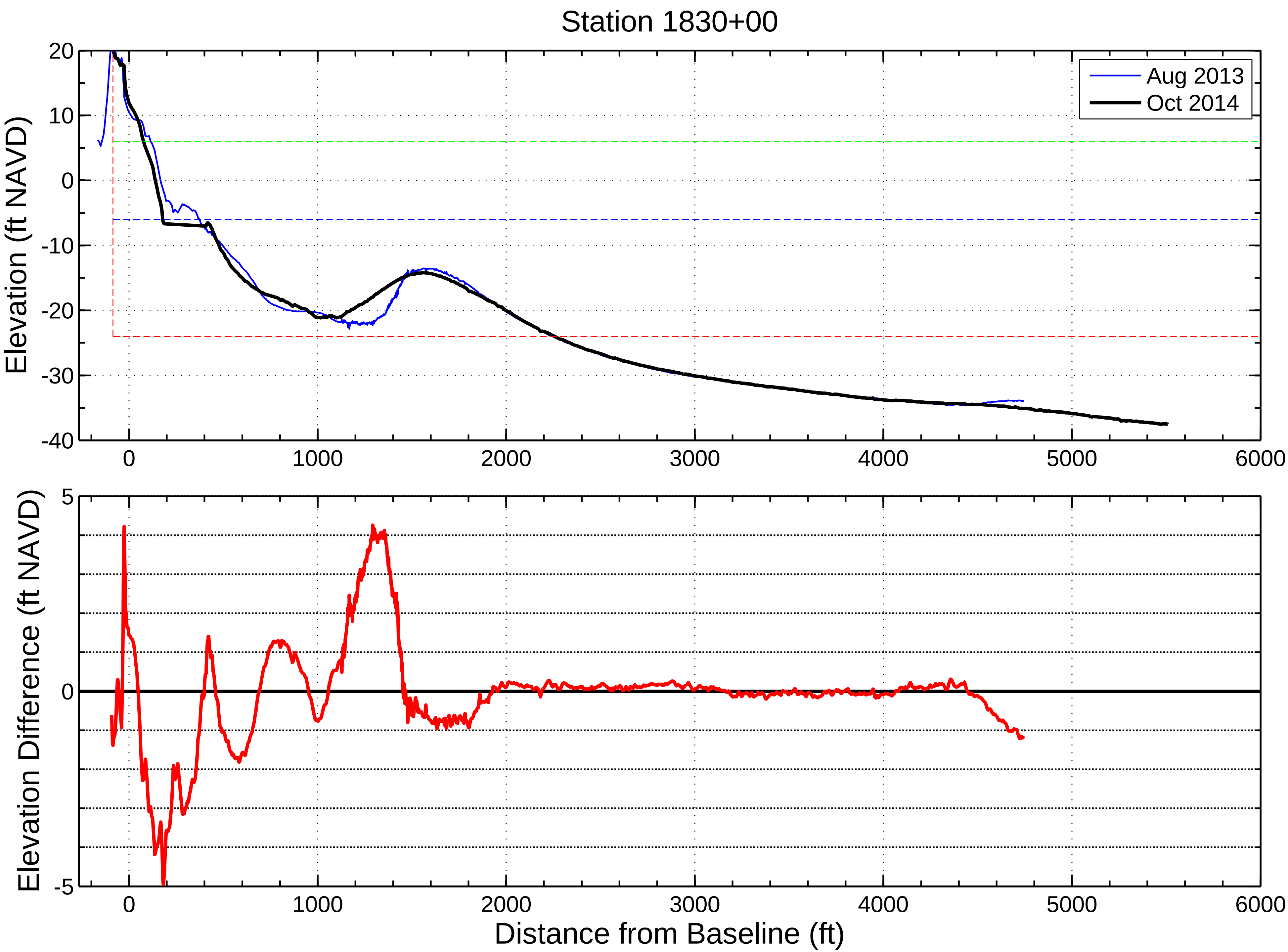

Station 1800+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)



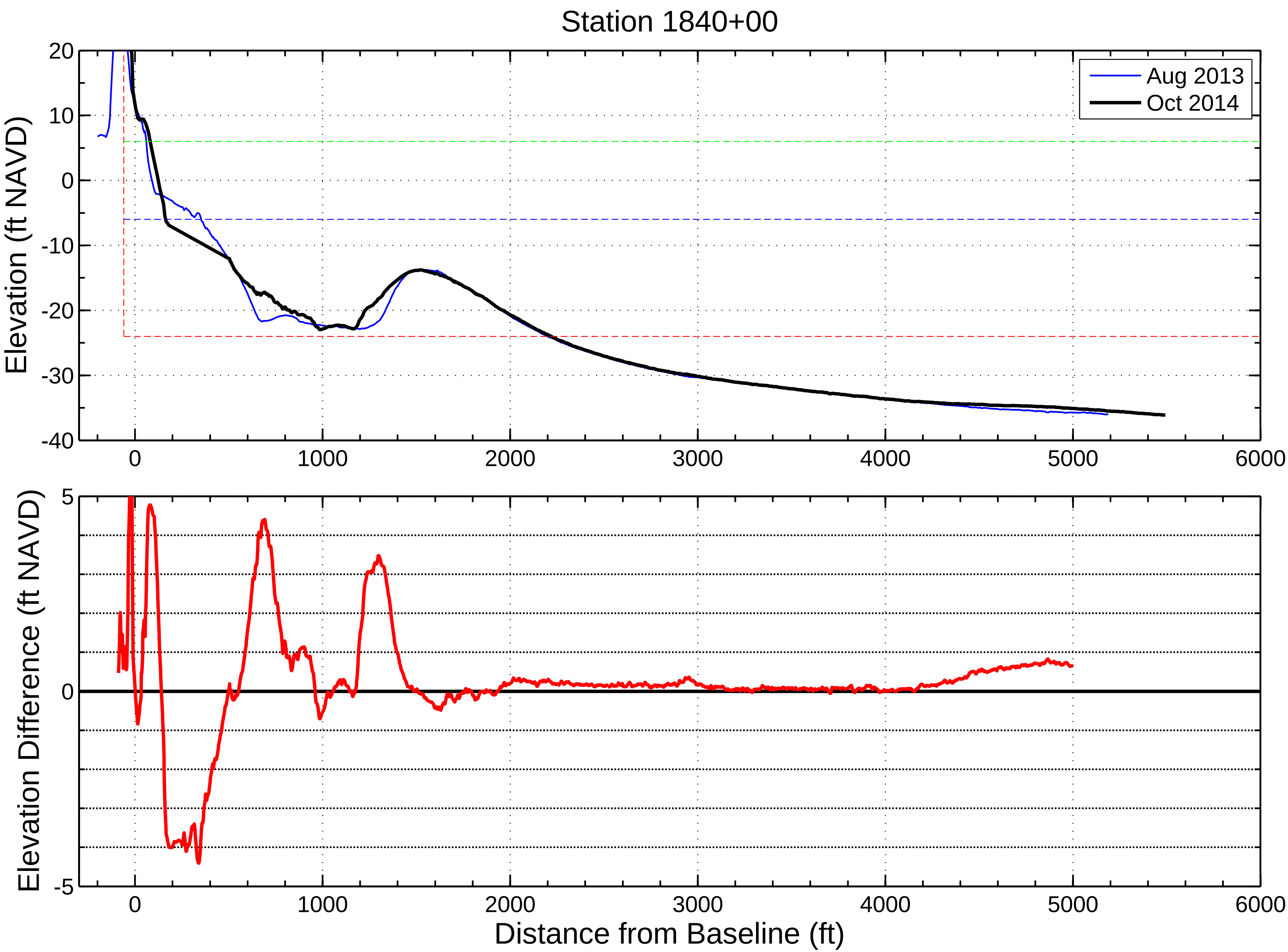
Station 1810+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)



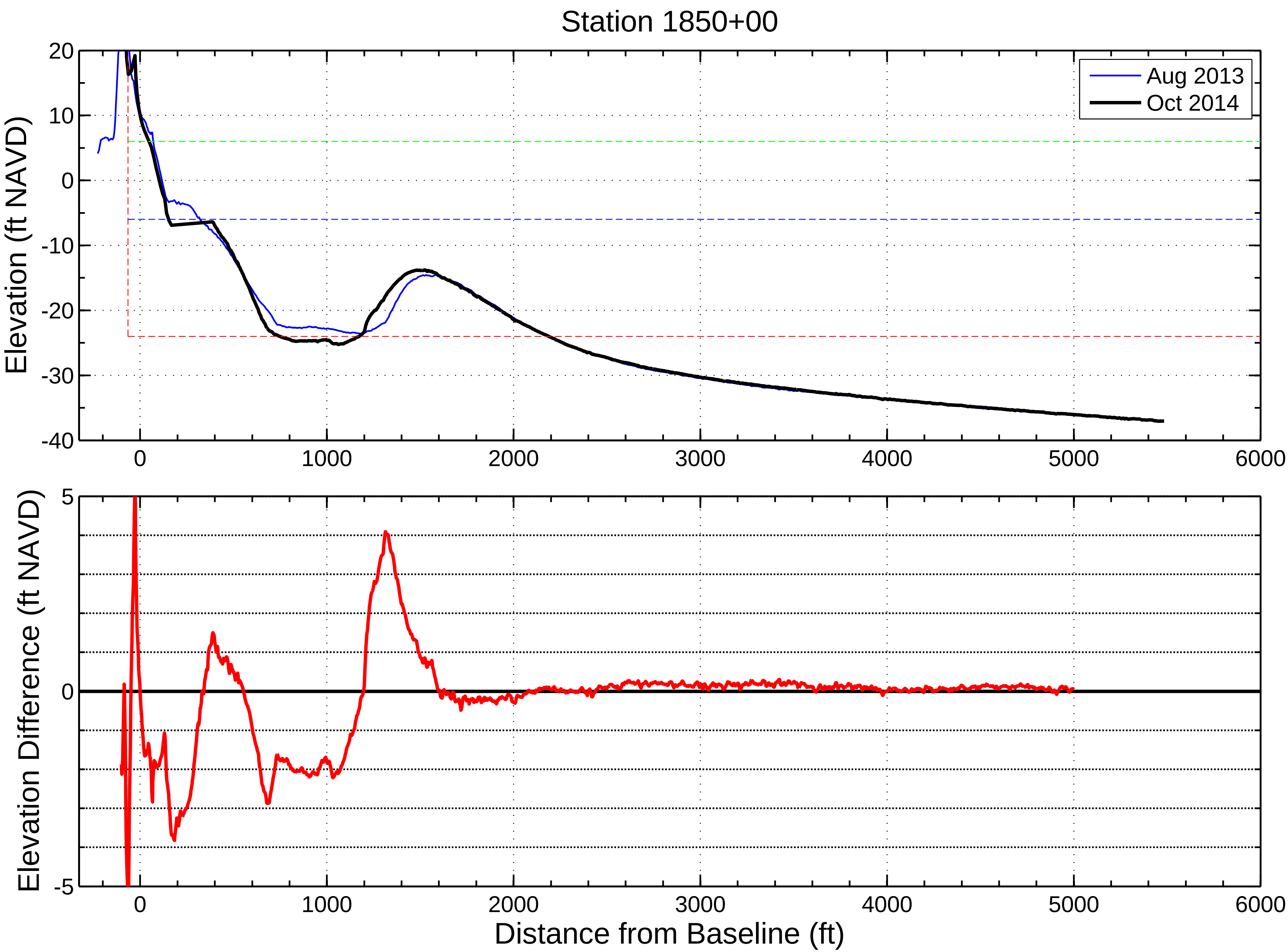
Station 1820+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)



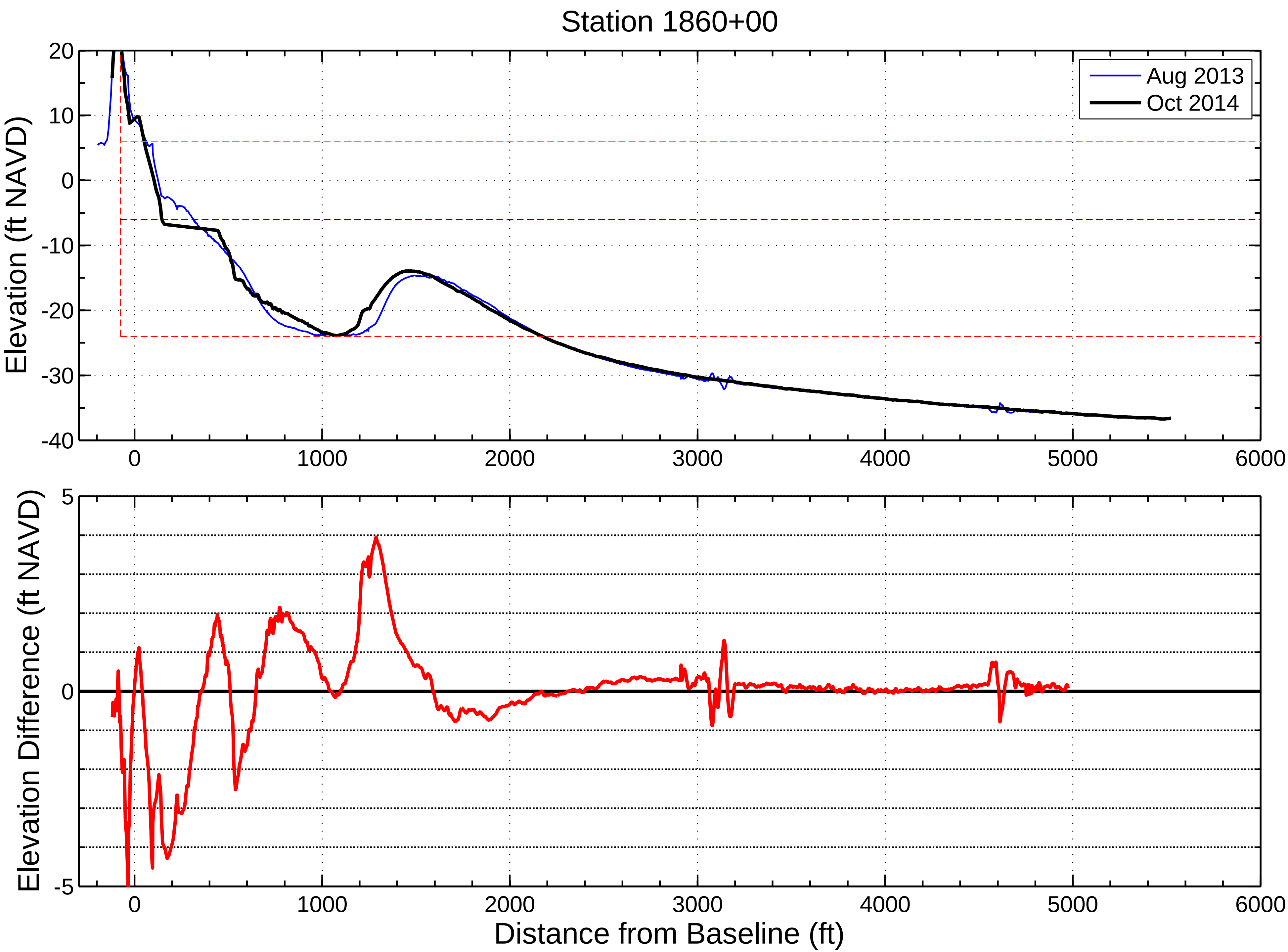
Station 1830+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
0
1000
2000
3000
4000
5000
6000
Distance from Baseline (ft)

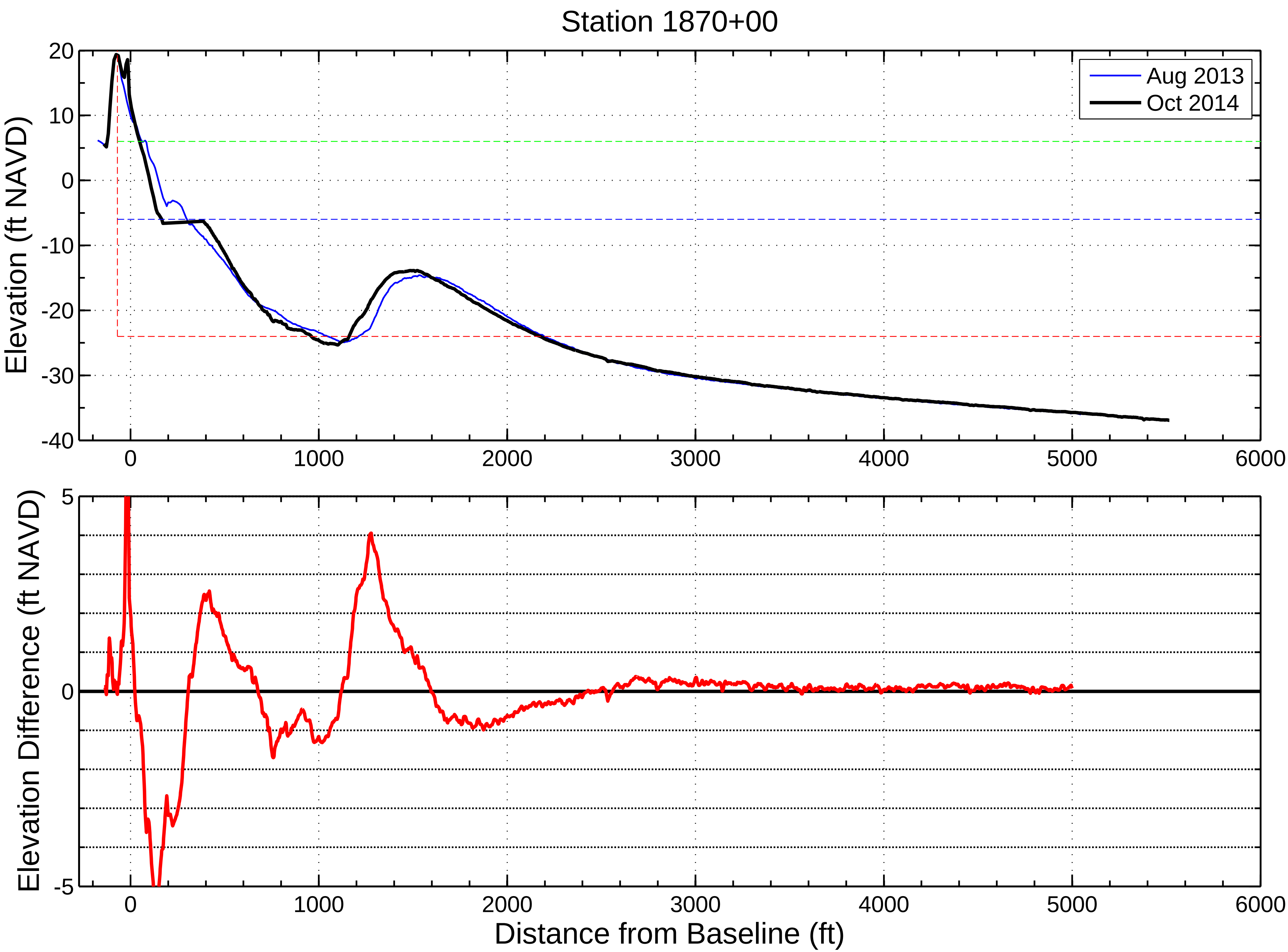


Station 1840+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)

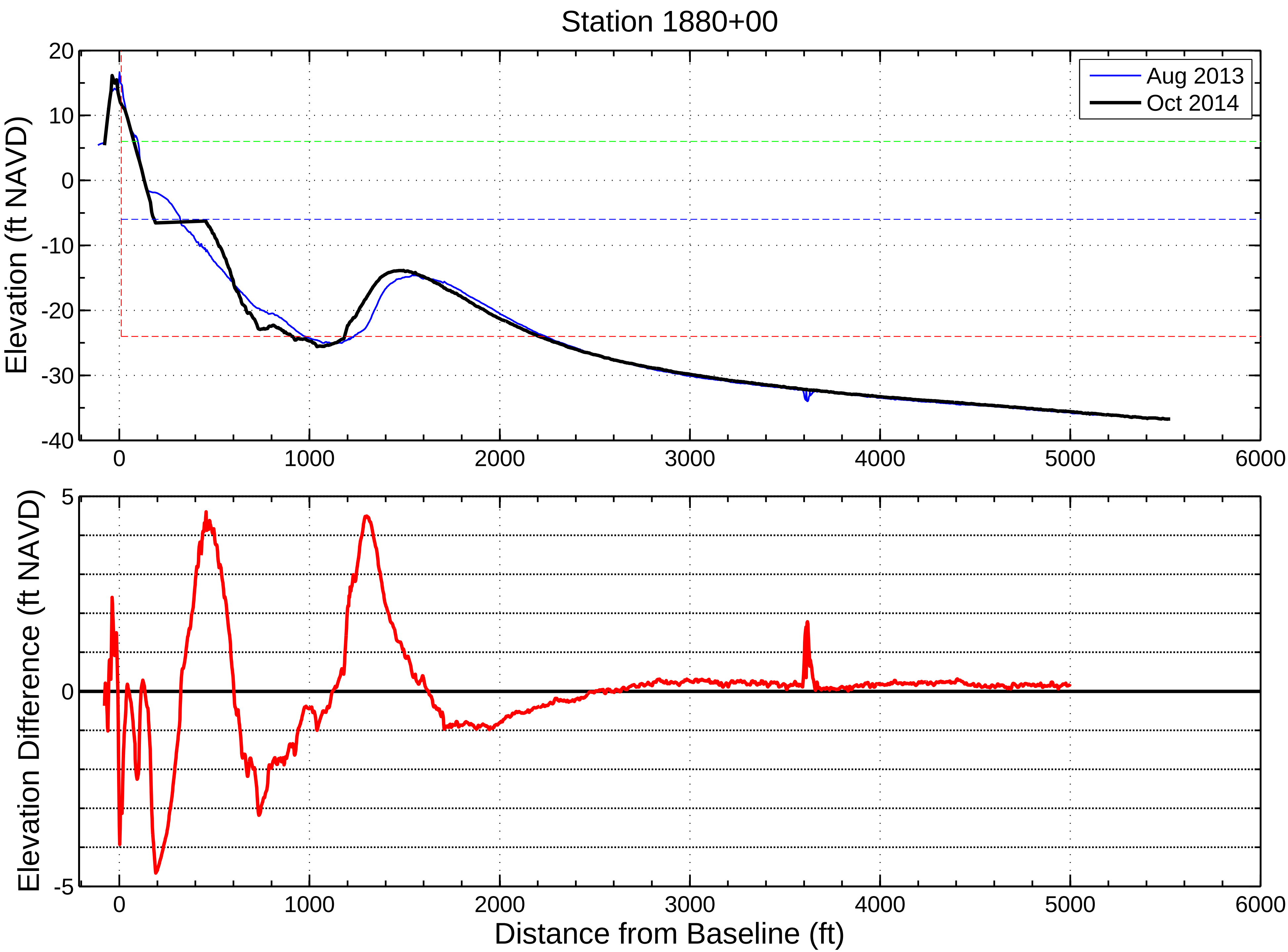


Station 1850+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
0
1000
2000
3000
4000
5000
6000
Distance from Baseline (ft)

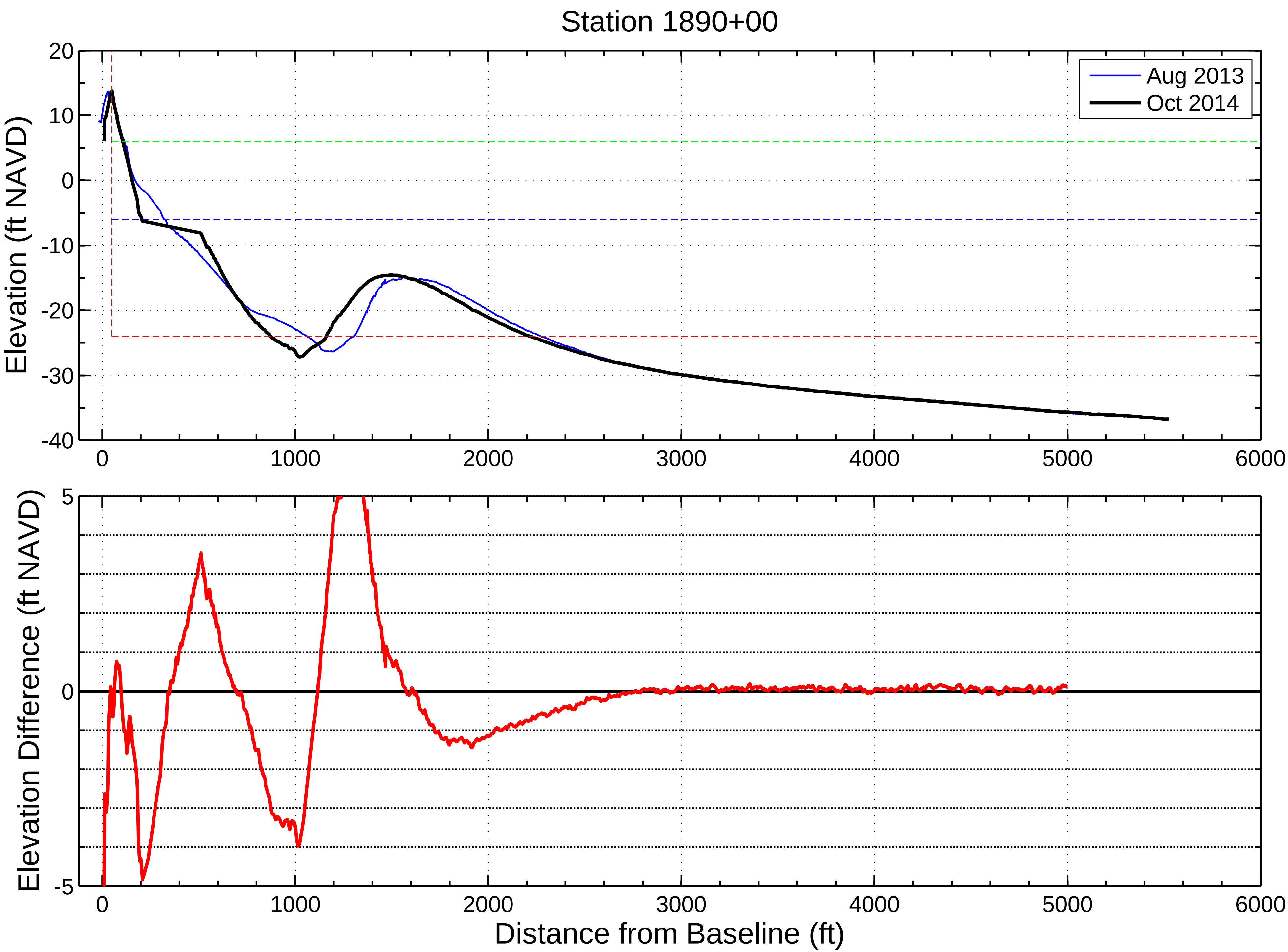

Station 1860+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
Elevation Difference (ft NAVD)
Distance from Baseline (ft)
20
10
0
-10
-20
-30
-40
5
0
-5
0
1000
2000
3000
4000
5000
6000



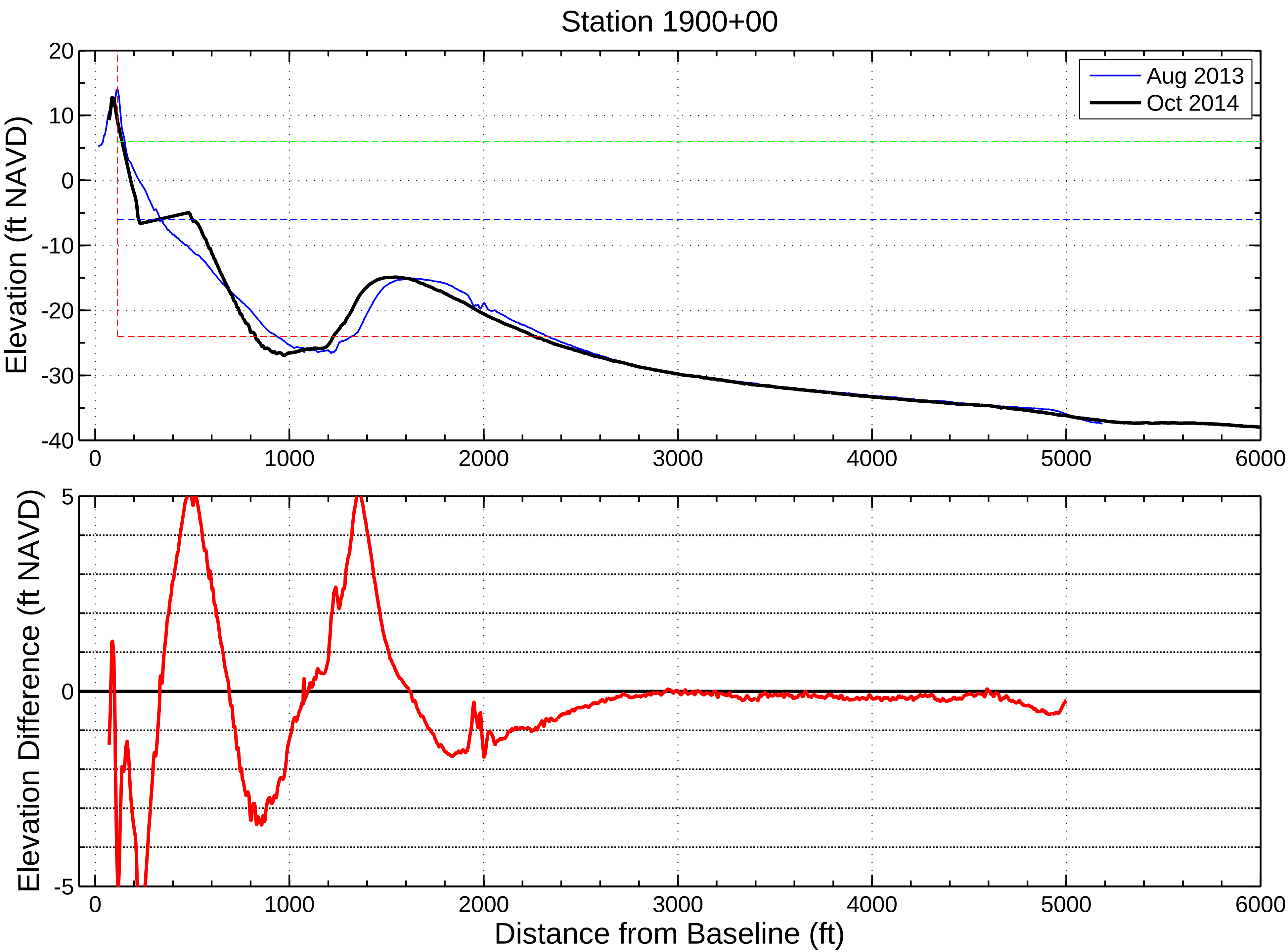
Station 1870+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)



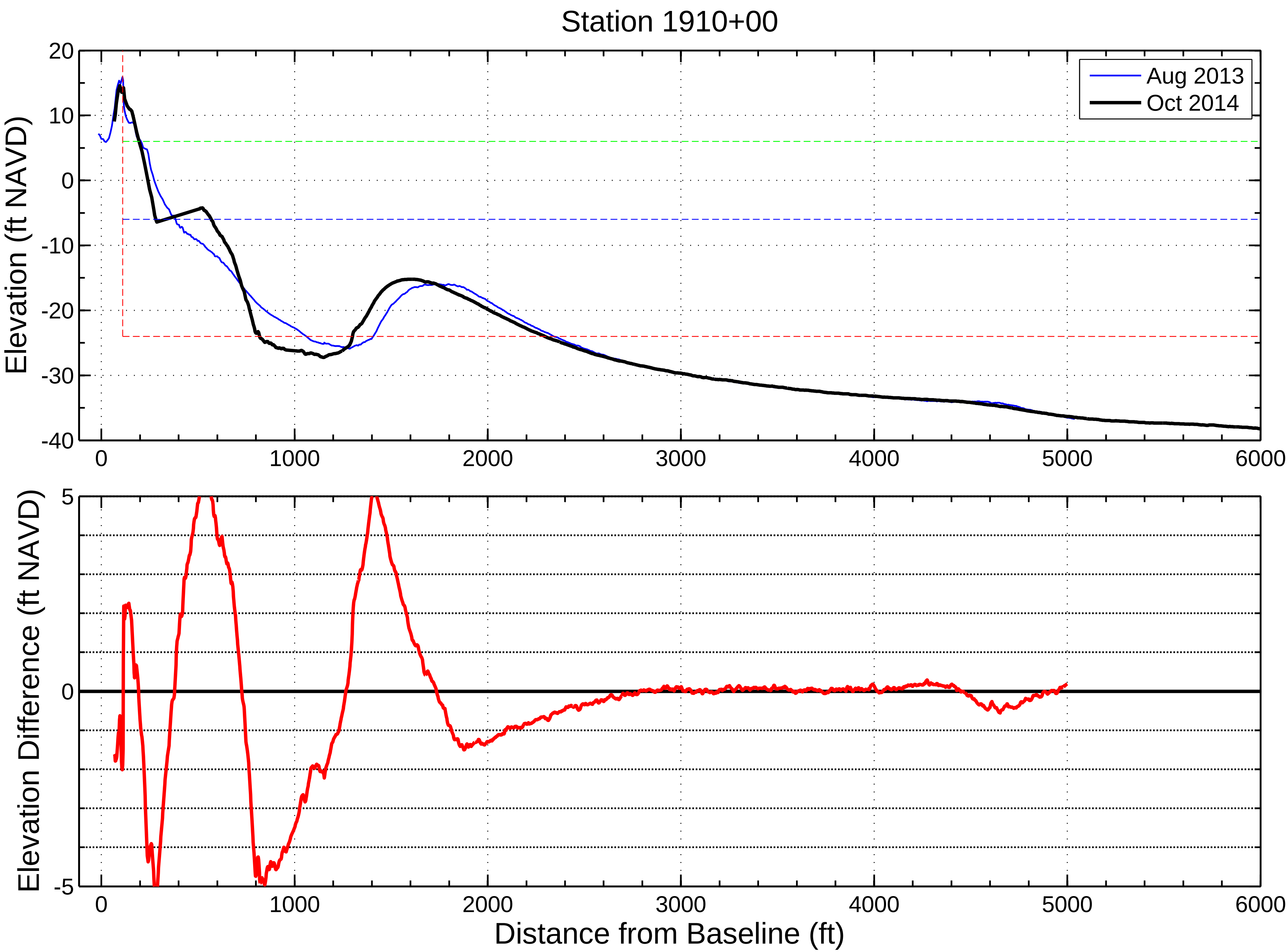
Station 1880+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)



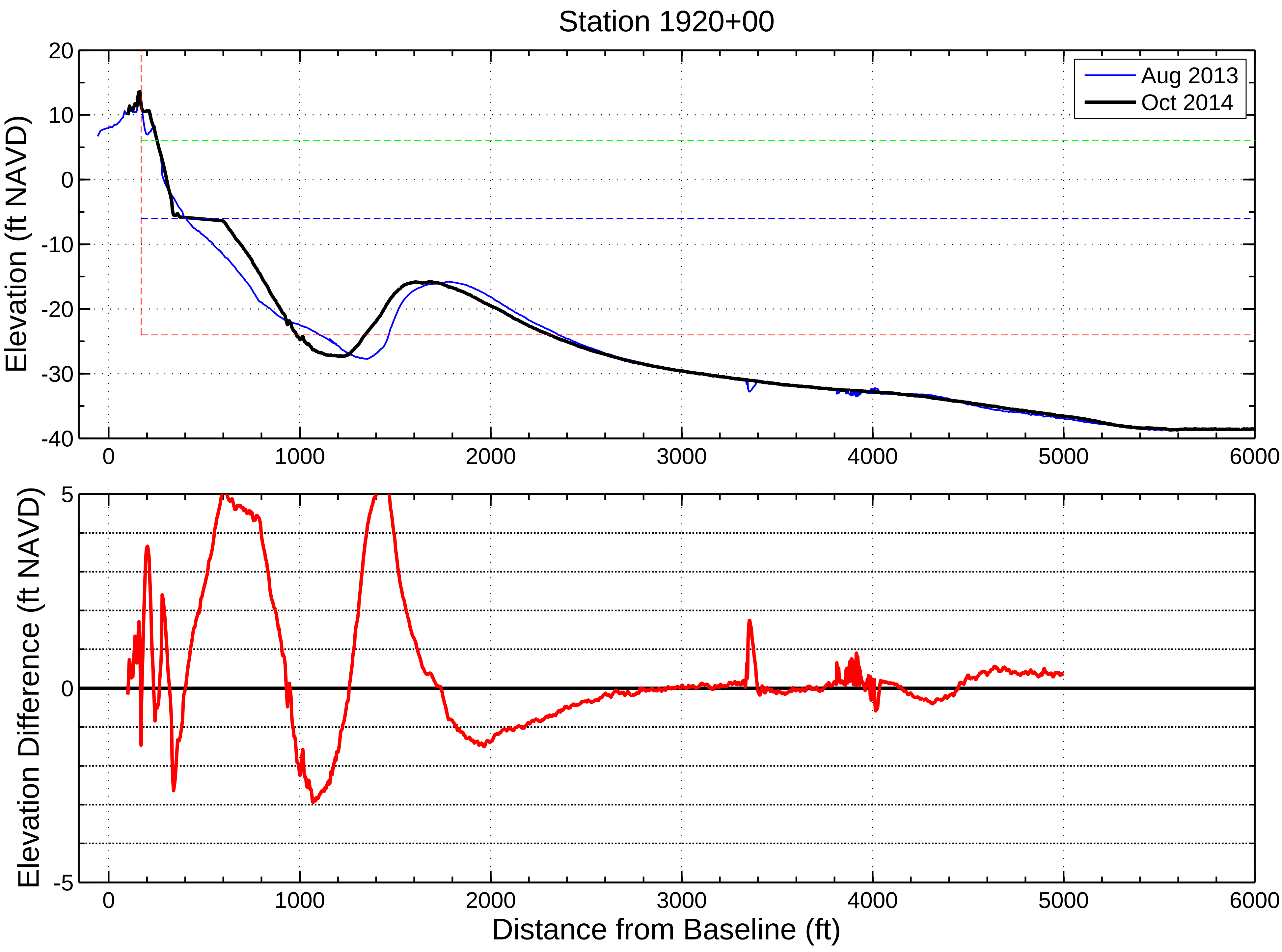
Station 1890+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)

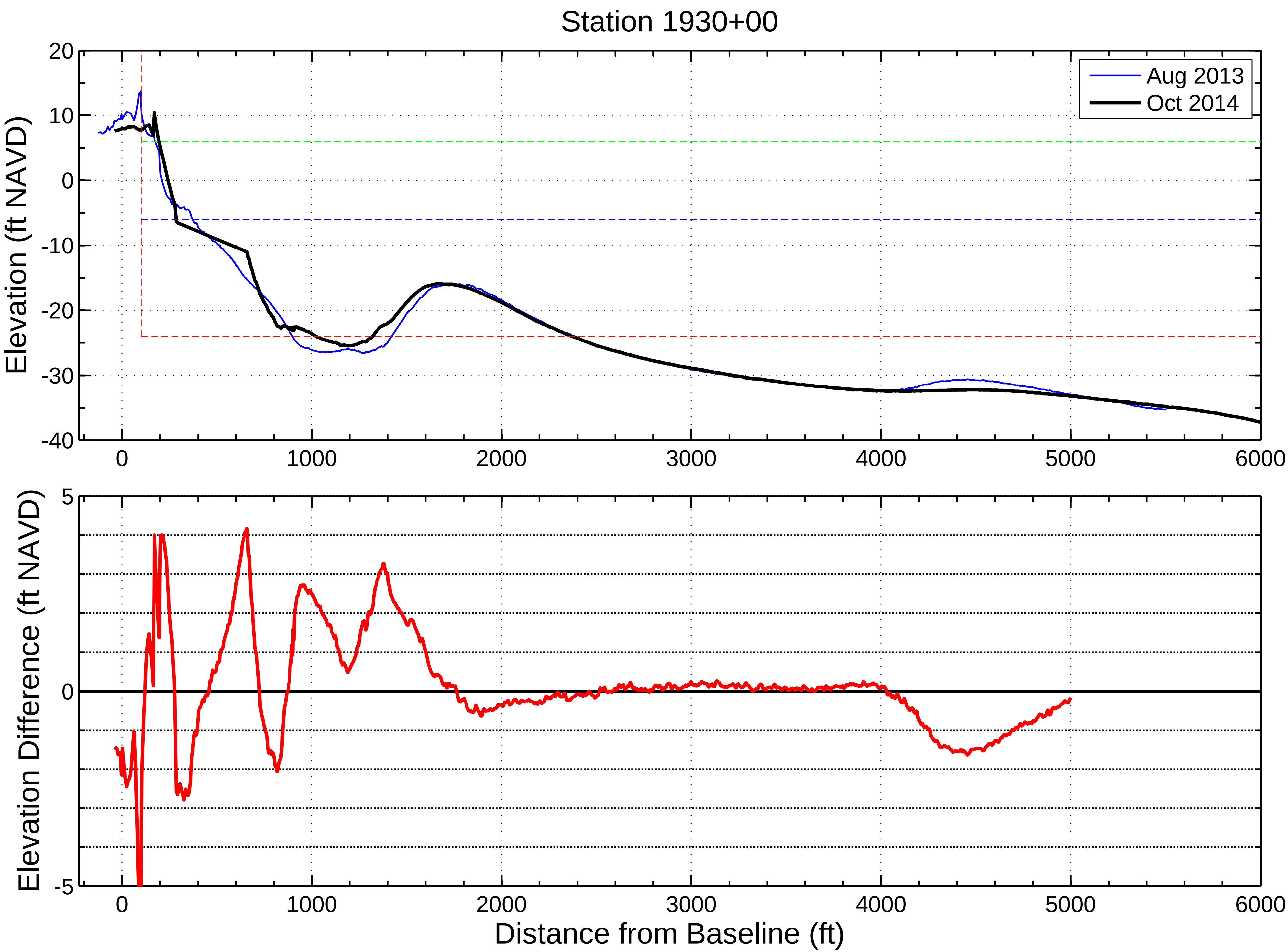


Station 1900+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)

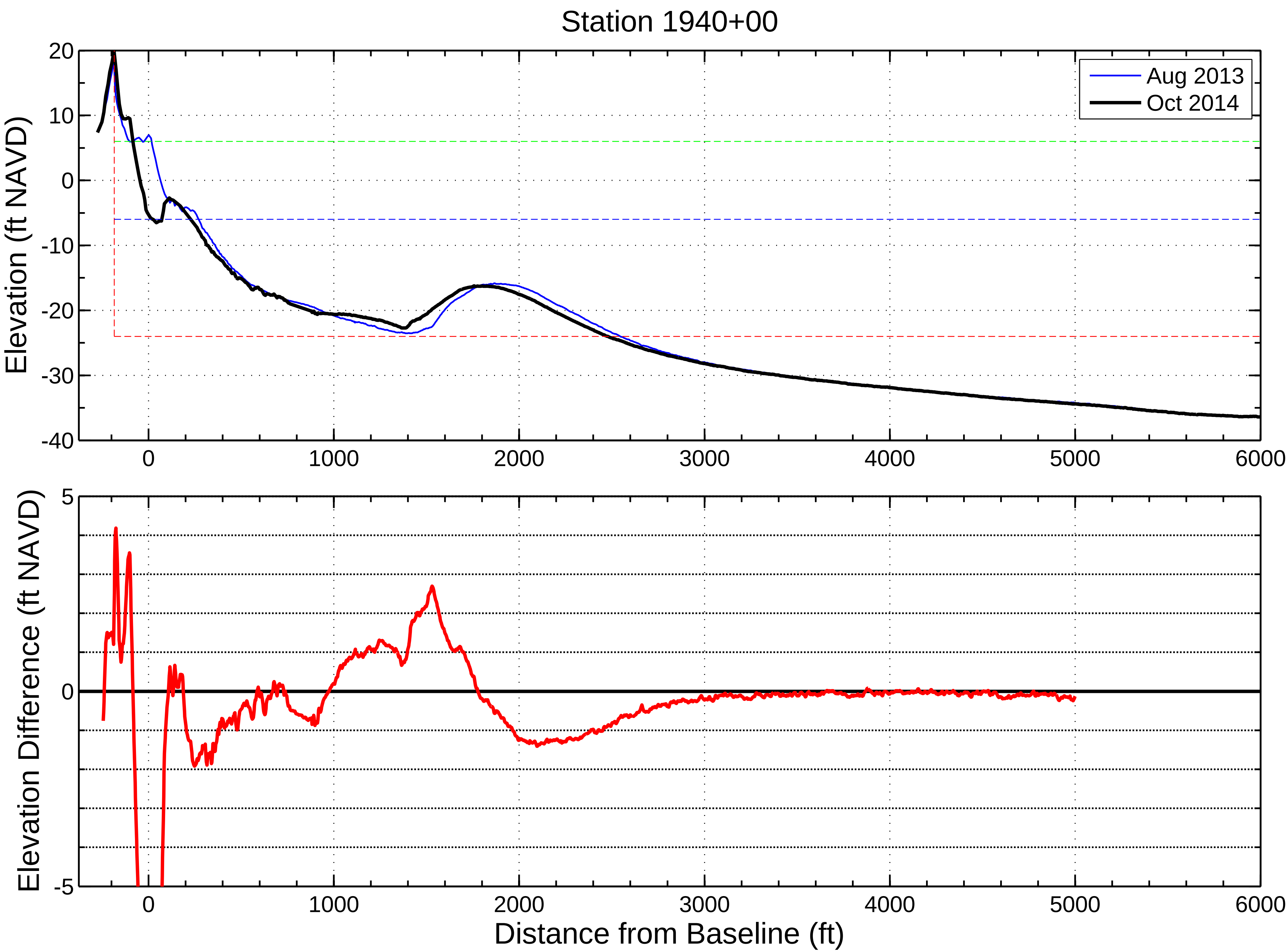


Station 1910+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)

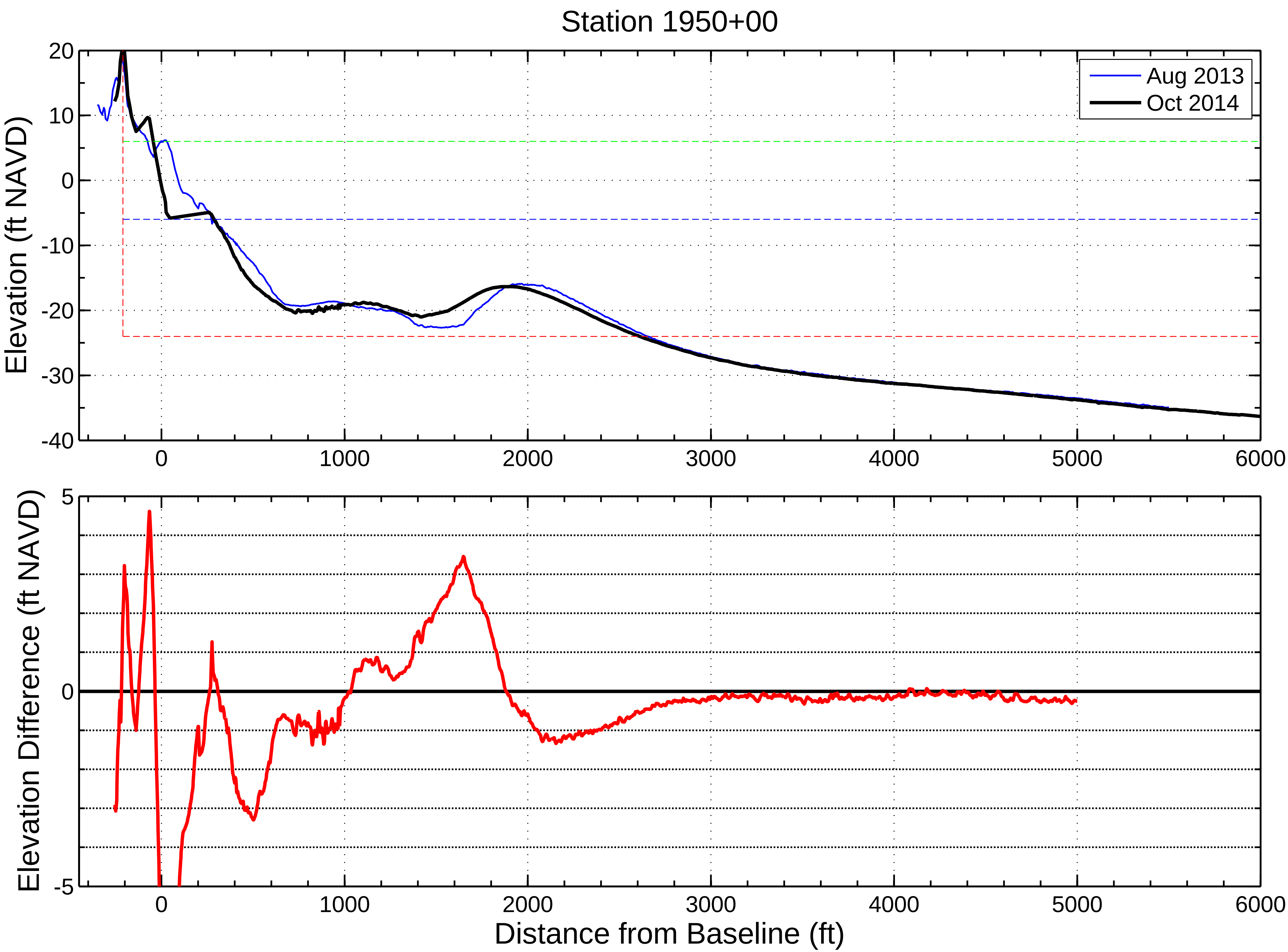

Station 1920+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)



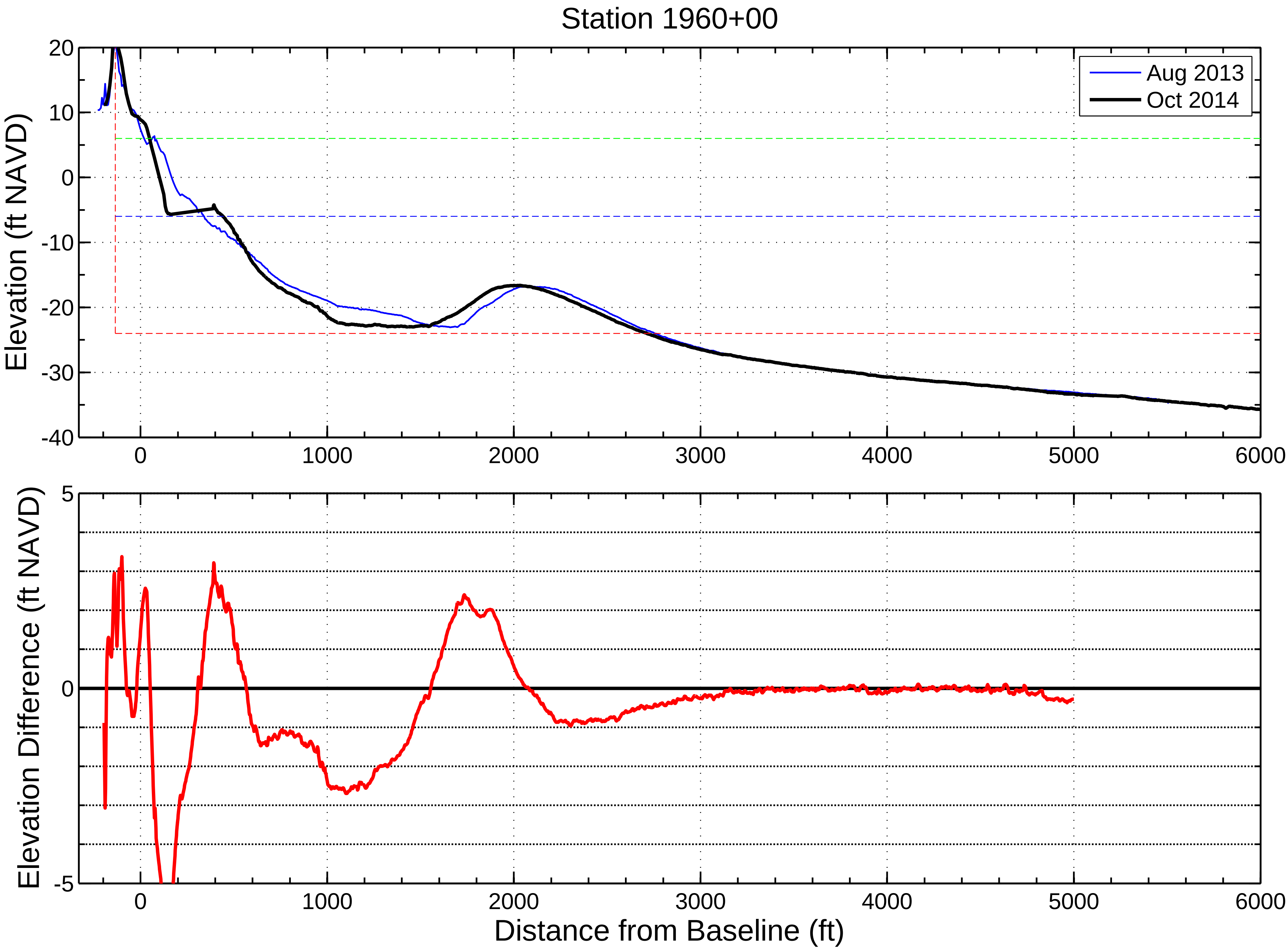
Station 1930+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)



Station 1940+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)

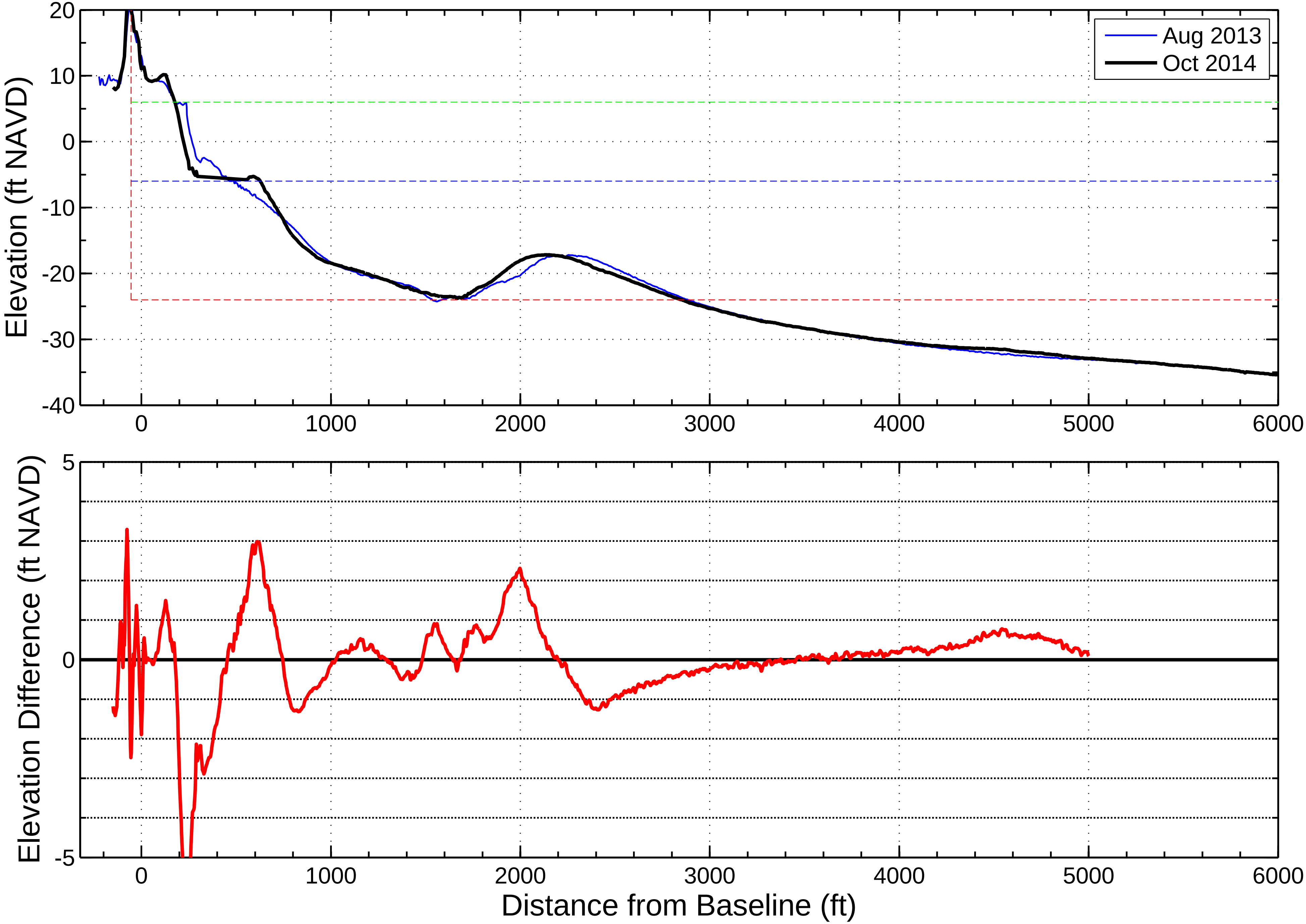


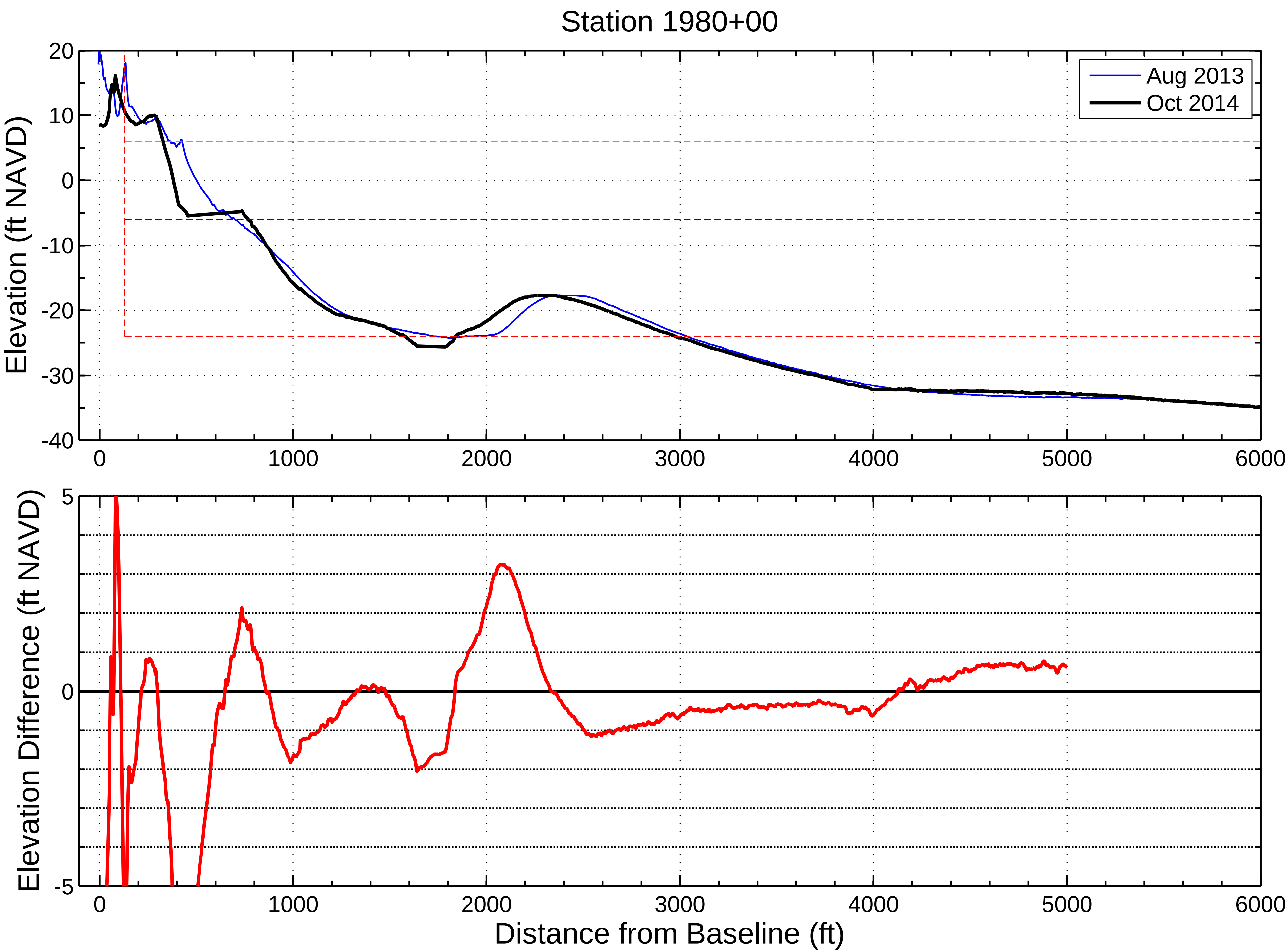
Station 1950+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)



Station 1960+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
0
1000
2000
3000
4000
5000
6000
Distance from Baseline (ft)

Station 1970+00

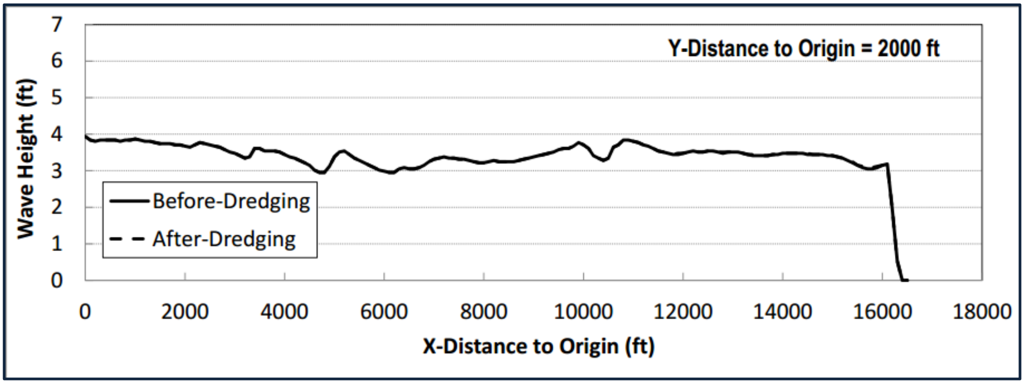


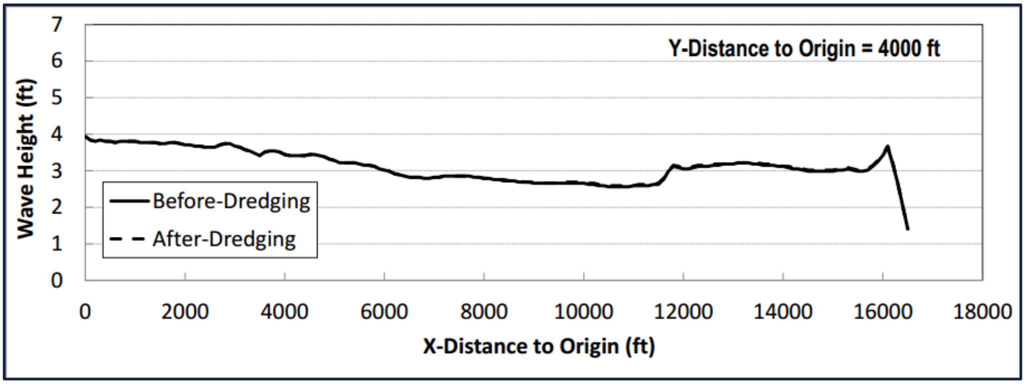


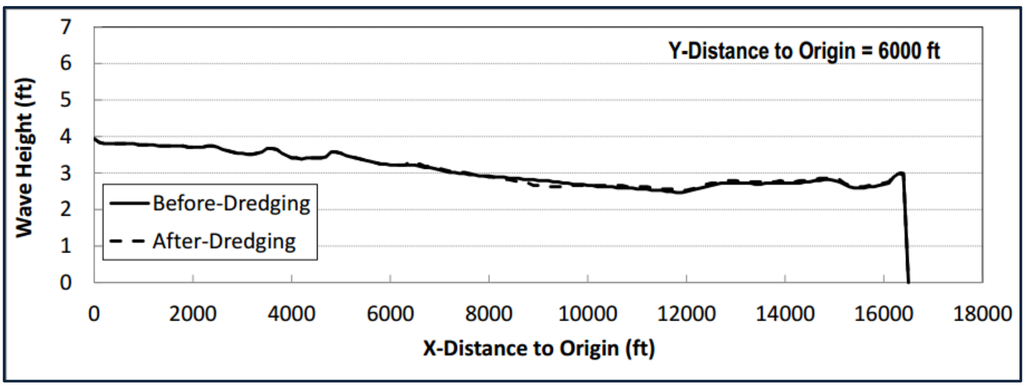
Station 1980+00
Aug 2013
Oct 2014
Elevation (ft NAVD)
20
10
0
-10
-20
-30
-40
0
1000
2000
3000
4000
5000
6000
Elevation Difference (ft NAVD)
5
0
-5
Distance from Baseline (ft)

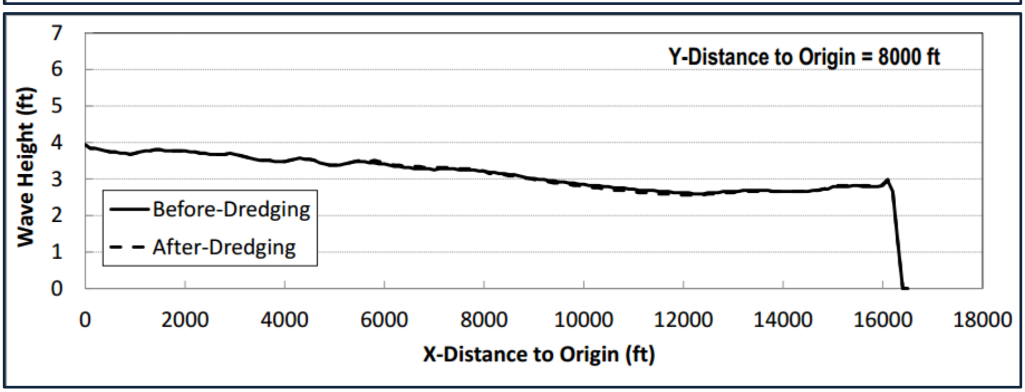
ATTACHMENT 6

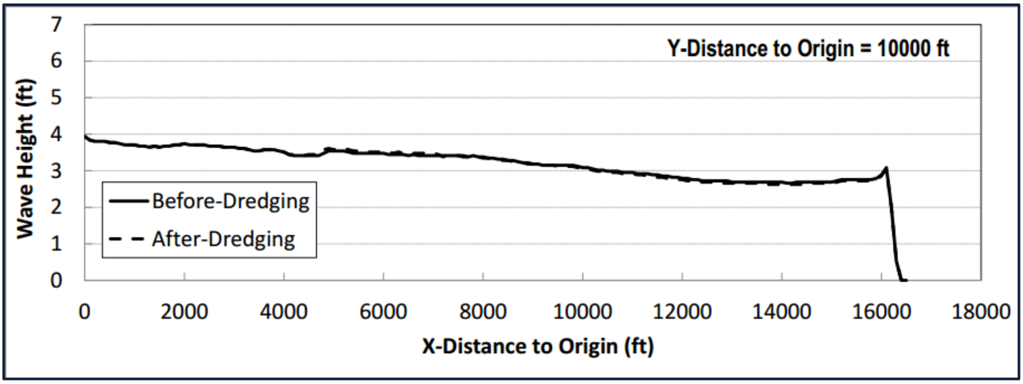
Additional STWAVE Results

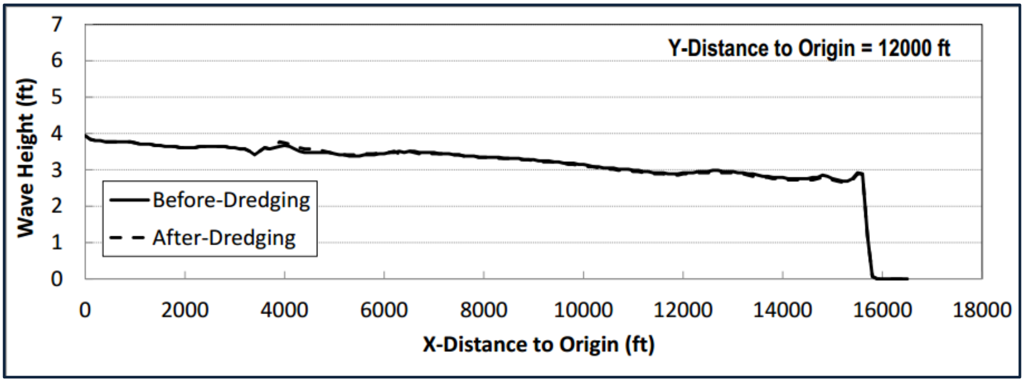

Y-Distance to Origin = 2000 ft
Wave Height (ft)
7
6
5
4
3
2
1
0
Before-Dredging
After-Dredging
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
X-Distance to Origin (ft)

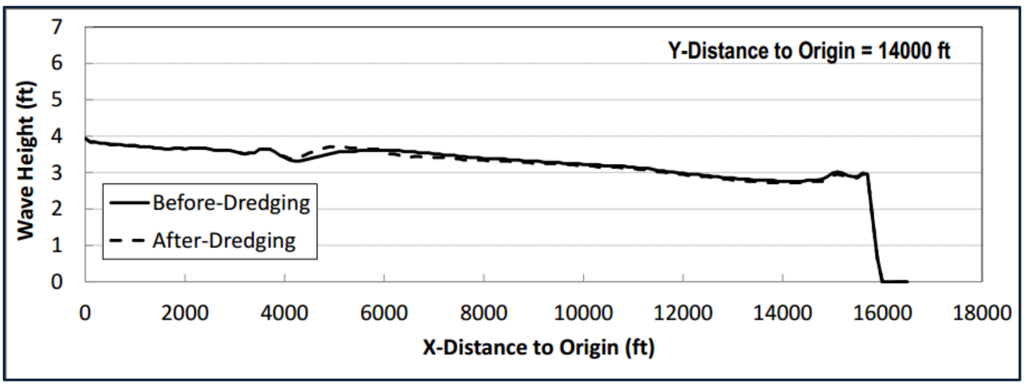

Y-Distance to Origin = 4000 ft
Wave Height (ft)
7
6
5
4
3
2
1
0
Before-Dredging
After-Dredging
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
X-Distance to Origin (ft)

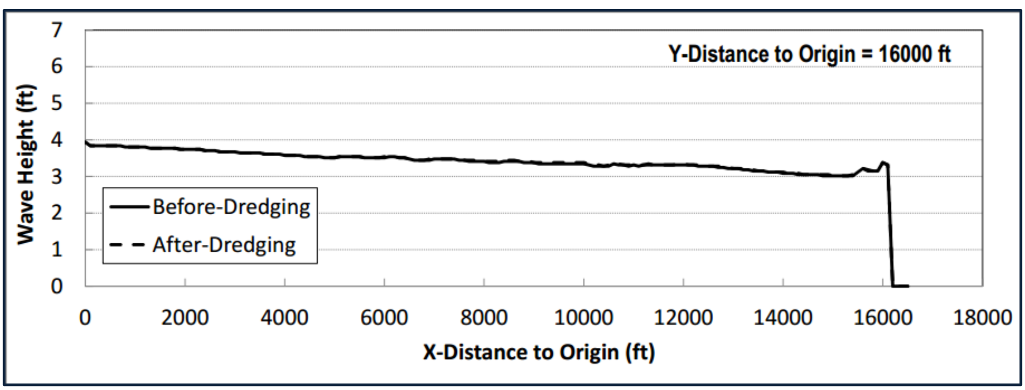

Y-Distance to Origin = 6000 ft
Wave Height (ft)
7
6
5
4
3
2
1
0
Before-Dredging
After-Dredging
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
X-Distance to Origin (ft)

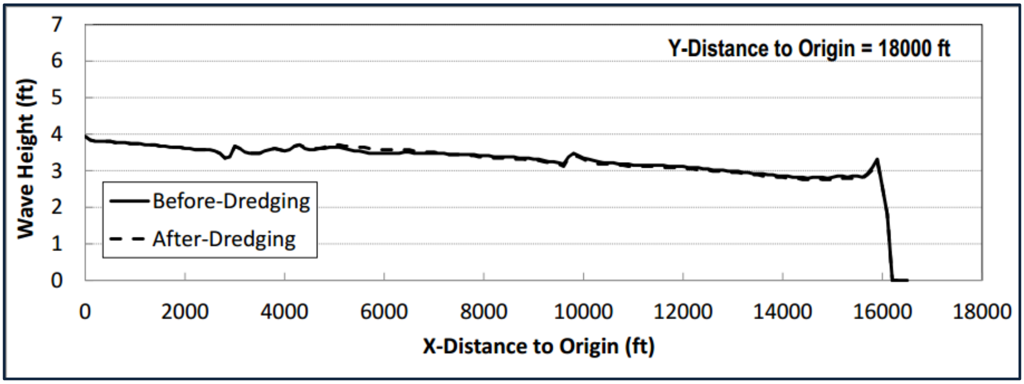

Y-Distance to Origin = 8000 ft
Wave Height (ft)
7
6
5
4
3
2
1
0
Before-Dredging
After-Dredging
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
X-Distance to Origin (ft)

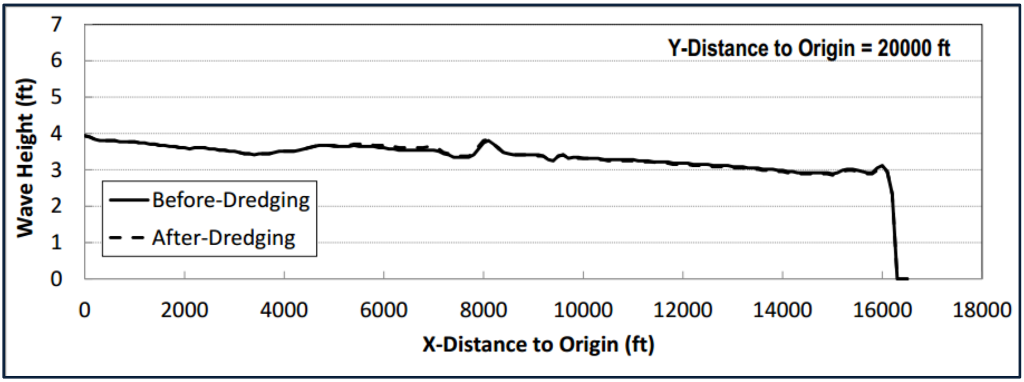

Y-Distance to Origin = 10000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

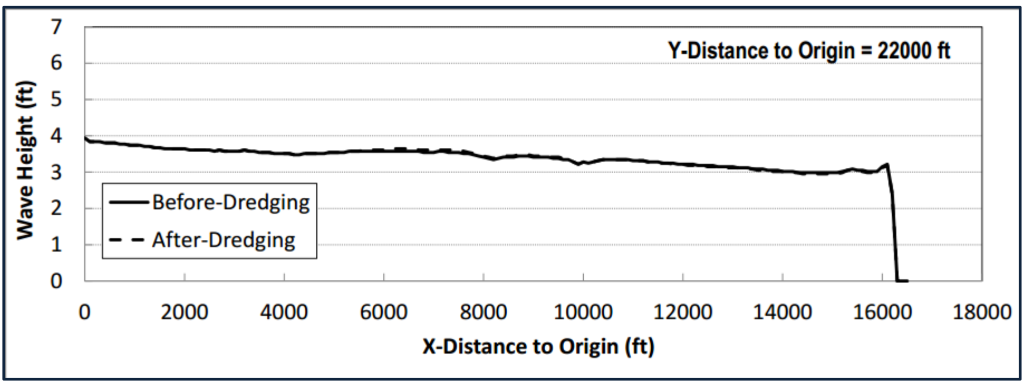

Y-Distance to Origin = 12000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

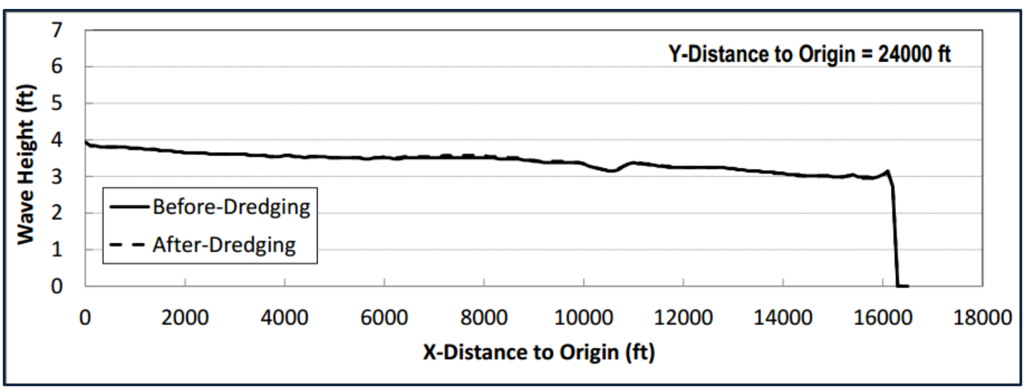

Y-Distance to Origin = 14000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

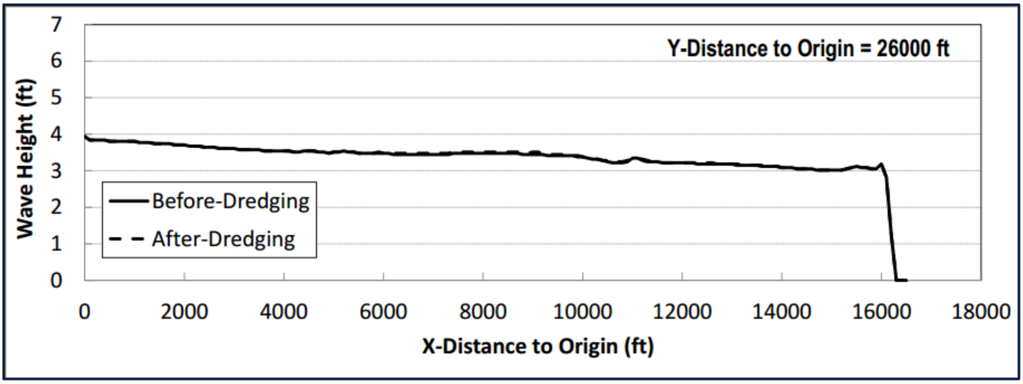

Y-Distance to Origin = 16000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

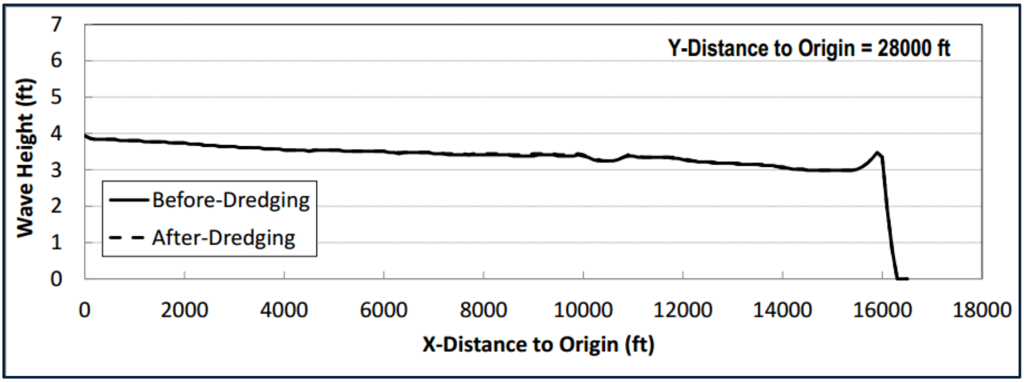

Y-Distance to Origin = 18000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging

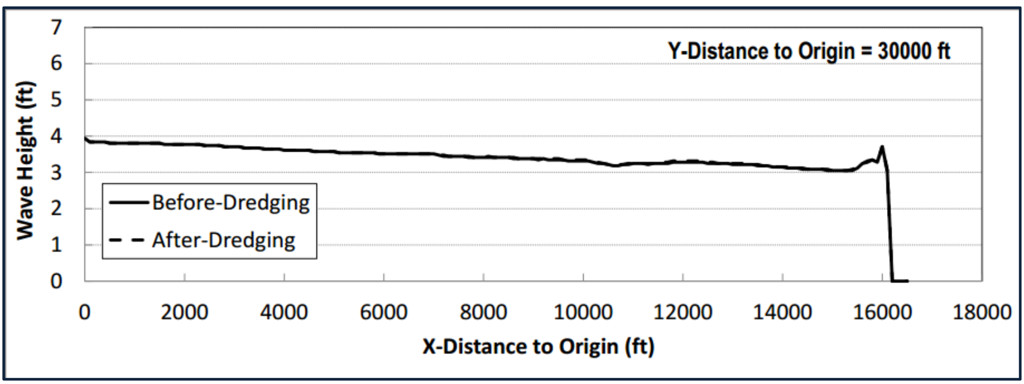

Y-Distance to Origin = 20000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging

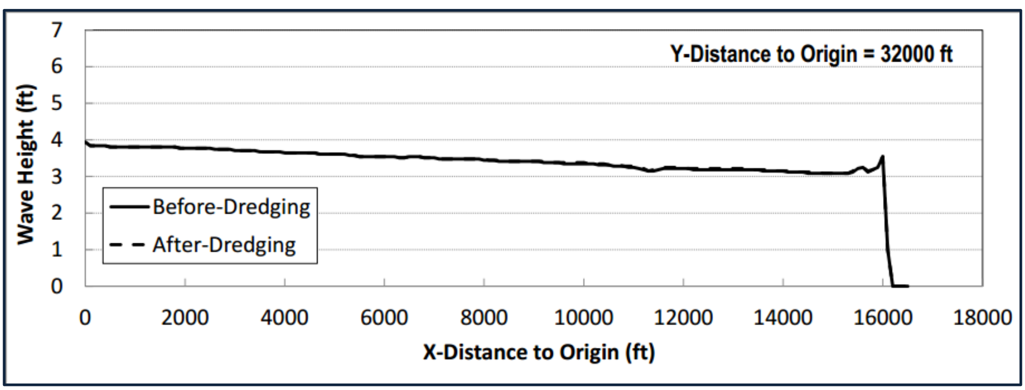

Y-Distance to Origin = 22000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging

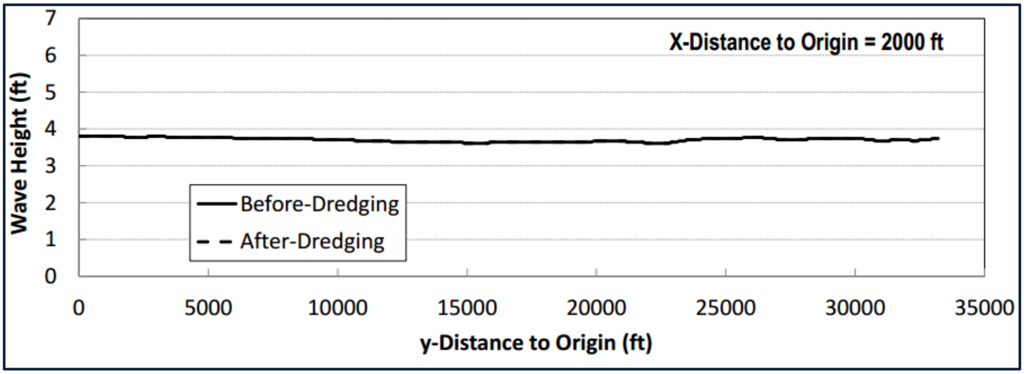

Y-Distance to Origin = 24000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging

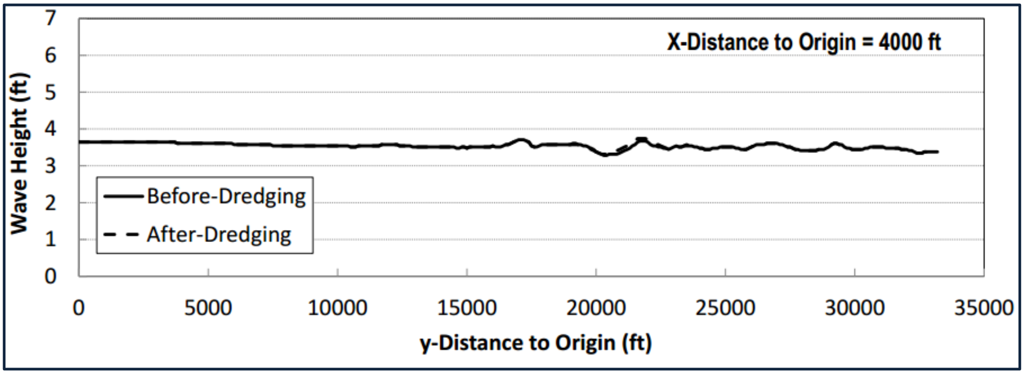

Y-Distance to Origin = 26000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

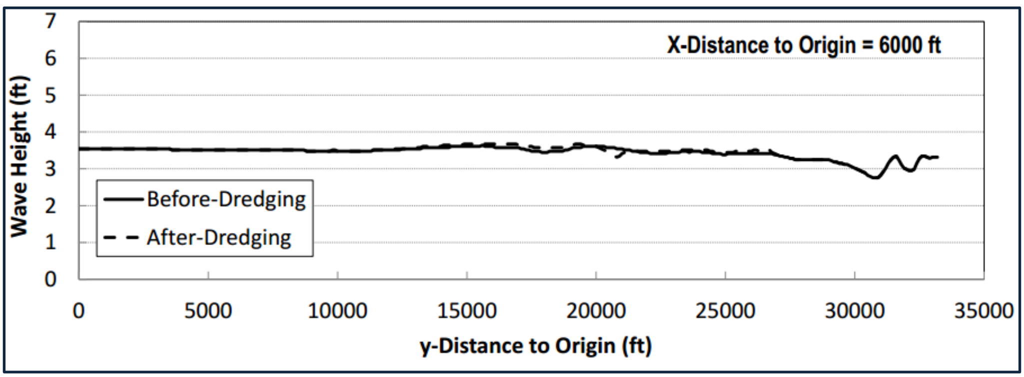

Y-Distance to Origin = 28000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

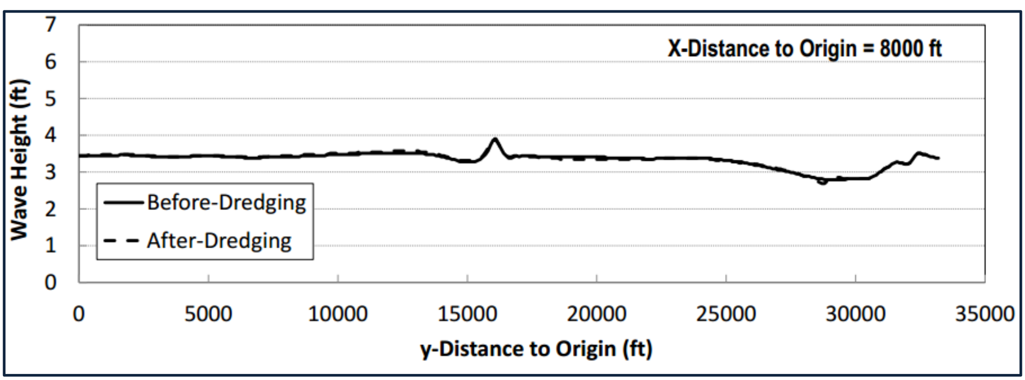

Y-Distance to Origin = 30000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

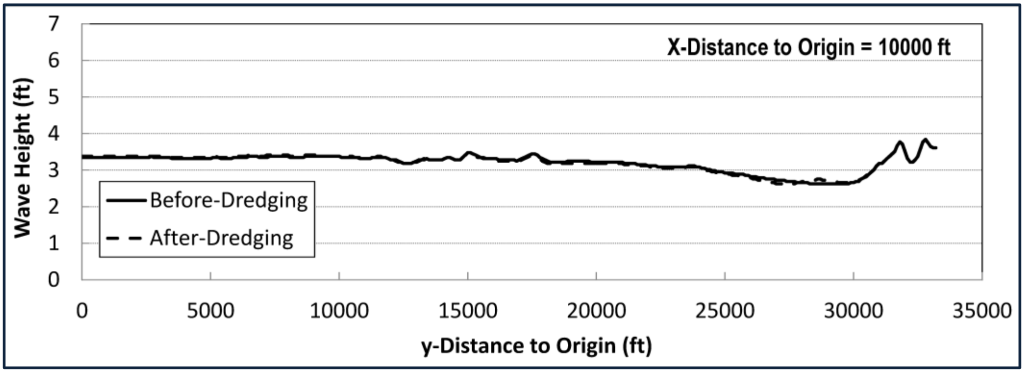

Y-Distance to Origin = 32000 ft
Wave Height (ft)
X-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
2000
4000
6000
8000
10000
12000
14000
16000
18000


X-Distance to Origin = 2000 ft
Wave Height (ft)
y-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
5000
10000
15000
20000
25000
30000
35000

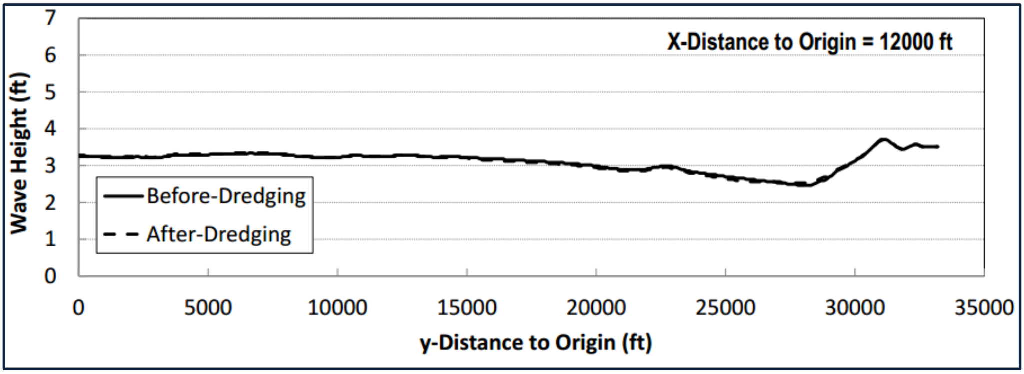

X-Distance to Origin = 4000 ft
Wave Height (ft)
y-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
5000
10000
15000
20000
25000
30000
35000


X-Distance to Origin = 6000 ft
Wave Height (ft)
y-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
5000
10000
15000
20000
25000
30000
35000

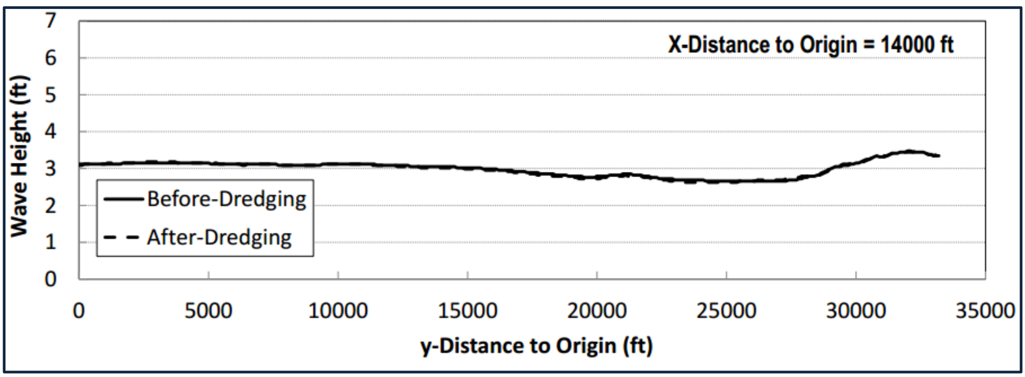

X-Distance to Origin = 8000 ft
Wave Height (ft)
y-Distance to Origin (ft)
Before-Dredging
After-Dredging
0
1
2
3
4
5
6
7
0
5000
10000
15000
20000
25000
30000
35000



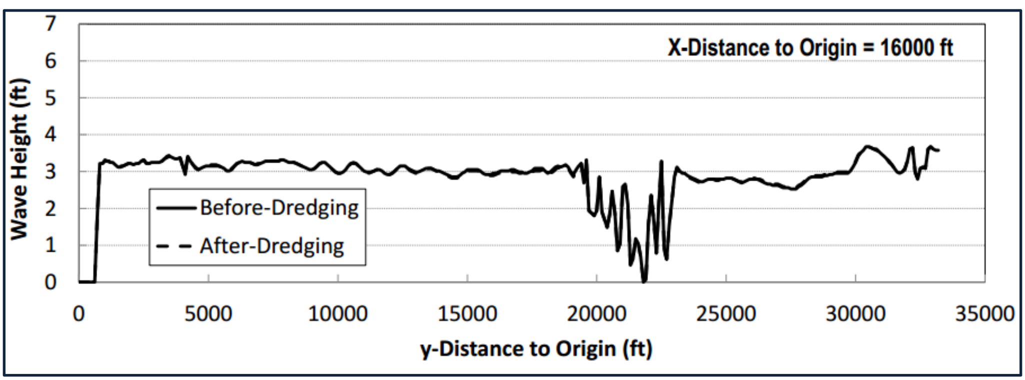
X-Distance to Origin = 10000 ft
Wave Height (ft)
y-Distance to Origin (ft)
Before-Dredging
After-Dredging



X-Distance to Origin = 12000 ft
Wave Height (ft)
y-Distance to Origin (ft)
Before-Dredging
After-Dredging



X-Distance to Origin = 14000 ft
Wave Height (ft)
y-Distance to Origin (ft)
Before-Dredging
After-Dredging



X-Distance to Origin = 16000 ft
Wave Height (ft)
y-Distance to Origin (ft)
Before-Dredging
After-Dredging