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Geomorphology and the Effects of Sea Level Rise on Tidal Marshes in Casco Bay

Curtis C. Bohlen PhD
University of Southern Maine, Casco Bay Estuary Partnership

Marla Stelk

Matt Craig
University of Southern Maine, Casco Bay Estuary Partnership

Lauren Redmond

Caitlin Gerber

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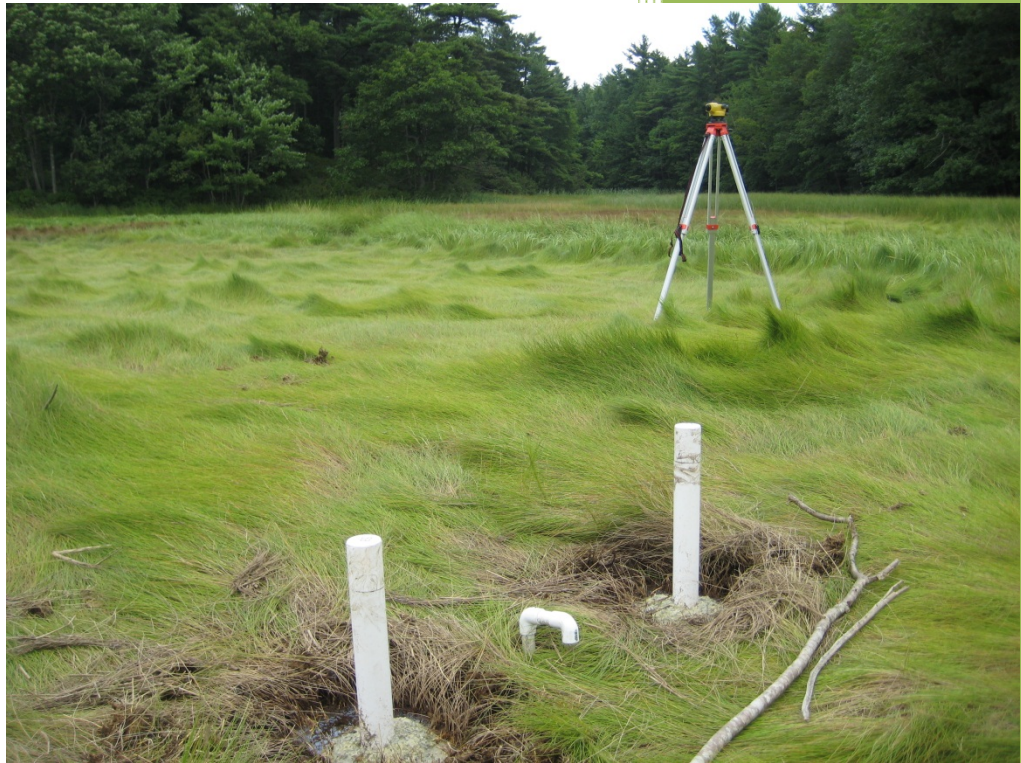
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Introduction

The geomorphology of the Casco Bay shoreline has a profound effect on the size, characteristics and spatial distribution of tidal marshes in the region. Casco Bay's steep shorelines and narrow, glacial cut coastal embayments provide relatively few opportunities for development of extensive salt marshes. On the basis of area and frequency, tidal marshes in the region are dominated by wetlands that form in glacier-cut coastal valleys. A smaller but still significant fraction of the tidal marsh area along the Casco Bay shorelines exists in a narrow, discontinuous ribbon of green perched between tidal waters and adjacent hillsides. This unique geomorphic setting means that lessons learned from evaluations elsewhere of vulnerability of tidal marshes to sea level rise provide limited insight into implications of sea level rise (SLR) for Casco Bay's wetlands.

In 2008, scientists from the Wells National Estuarine Research Reserve hand delineated small fringing marshes along most of the Casco Bay shoreline, based on aerial photography. The data they developed suggests that on the order of 10% of Casco Bay's tidal marshes are so small, narrow, or discontinuous that they are not included in the National Wetland Inventory map products.¹ They also provided preliminary evaluation of the impact of sea level rise on a subset of tidal marshes, based on field surveys of marsh microtopography. Their findings suggested that responses of tidal marshes to sea level rise in the Casco Bay region will be complex, with some marshes increasing in area due to inundation of adjacent uplands, others reduced in area as they are flooded too deeply to maintain wetland vegetation, and still others showing shifts from dominance of high marsh vegetation to dominance by low marsh vegetation.

Because of this complex response, and indications in the data that the response of wetlands to sea level rise may be correlated with marsh size, it was, at that time, deemed impossible to evaluate the overall impact of inundation on Casco Bay's wetlands. Recent availability of high resolution LIDAR data for the Casco Bay coast, however, has provided an opportunity to take a closer look at how tidal marshes in the region may respond to changing sea levels.

Project Goals

1. Develop preliminary inundation maps based on LIDAR coverage to correspond to present-day sea level, and one foot, two foot, and three foot sea level rise scenarios.
2. Analyze SLR scenarios as applied to substantially all marshes in Casco Bay including fringing marsh and head of valley marshes to improve our understanding wetland gains and losses under SLR scenarios.
3. On a subset of wetlands, examine the sensitivity of predictions of responses to SLR based on sediment accretion assumptions.
4. Evaluate effects of SLR on a subset of tidal marshes with tidal restrictions and use LIDAR data to characterize relative tidal marsh surface elevations upstream and downstream of restrictions.
5. Evaluate if and how tidal marsh restoration priorities should be revised based on SLR considerations and improved elevation models (LIDAR).

¹Hayes, Peter, Rachel Carr, Michele Dionne. 2008. Project Report: Mapping and Restoration Inventory of Fringing Marsh Habitat in the Casco Bay Estuary. Available at http://www.cascobay.usm.maine.edu/habitat_fringing_marsh.html

6. Communicate results and findings to local towns, land trusts, conservation groups and others considering wetland restoration efforts and efforts to protect upland areas to allow landward migration of tidal wetlands.

Organization of This Report

This report is organized around major project tasks and deliverables as follows:

- (1) Development of coastal inundation data and associated wetland data layers predicting present and future extent of tidal wetlands;
- (2) Use models to explore sensitivity of wetland response to sea level rise on sediment accretion rates;
- (3) Development and demonstration of techniques for use of LIDAR data to support evaluation of restoration opportunities at tidal restrictions around Casco Bay;
- (4) Development of outreach materials to areas communities about how wetlands in their communities may be influenced by sea level rise and identifying locations where future expansion of tidal marshes may conflict with existing land use.

Part 1: Development of Wetland Migration Map Data

Sea Level Rise Scenarios

Maine Geological Survey (MGS) and the Maine Natural Areas Program (MNAP) have completed an evaluation of how the largest tidal marshes (greater than 5 acres) in Casco Bay would respond to sea level rise. As part of that effort, they used available LIDAR coverage to identify areas of the Casco Bay coast vulnerable to inundation under 2 foot and 1 meter sea level rise scenarios.

CBEP developed complementary data layers depicting the area of inundation under one foot, two foot, and three foot sea level rise scenarios. We decided to base our work on English rather than metric units of measure because a key target audience for the results of our study is local communities, and most Americans are more comfortable working in feet than in meters. While these scenarios are not tied to specific climate change or sea level rise models, they are consistent with modeling efforts. A recent analysis of climate change for the Casco Bay region commissioned by CBEP² suggests that increases in sea level on the order of one foot are likely by the middle of the century, while increases of two to well over three feet are possible by 2100 (See Table 1).

The one foot level is close to current expectations in the scientific community for sea level rise by mid-century, and thus is of interest to town planners and others interested in relatively short term (2-3 decade) planning horizons. However, one foot sea level rise hovers right at the edge of the margin of error for the LIDAR data on which this project is based, so the data should be interpreted with special care. A two foot sea level rise represents something like a high end estimate of sea level rise to be seen by 2050 or, alternatively, a moderately conservative estimate of sea level rise anticipated by the end of the century. Three feet of sea level rise is moderately likely by the end of the century, and represents the outer range of what we thought current policy makers would want to consider for planning purposes. It is important, however, to remember

² Wake, C., Burakowski, E., Hayhoe, K., Watson, C., Douglas, E., VanDorn, J., Naik, V. and C. Keating. 2009. Climate Change in the Casco Bay Watershed: past, present, and future (p. 43). Portland, ME. Retrieved from http://www.cascobay.usm.maine.edu/pdfs/Climate_Change_in_Casco_Bay.pdf

that sea levels are expected to continue to rise beyond the end of the century, so levels well above three feet are likely to occur eventually.

Table 1: Estimates of future stillwater elevations at the Portland tide gauge under lower and higher greenhouse gas emissions scenarios (all estimates in feet relative to NAVD 1988).

Scenario	Lower Emissions		Higher Emissions	
	2050	2100	2050	2100
FEMA 1998 Stillwater Elevation	8.9	8.9	8.9	8.9
Subsidence	0.024	0.043	0.024	0.043
Dynamic	NE	0.52	NE	0.79
Eustatic	0.66	1.6	1.4	4.6
Total Predicted Stillwater Elevation	9.5	11.1	10.3	14.3
Net Change in Sea Level	0.6	2.2	1.4	5.4

The Study Area

We focused our attention on the shores of Casco Bay, including the shores of the Casco Bay islands. In practice, we prepared geographic data that covered most of the Casco Bay coastal region. Figure 1 provides a map of our primary study area.

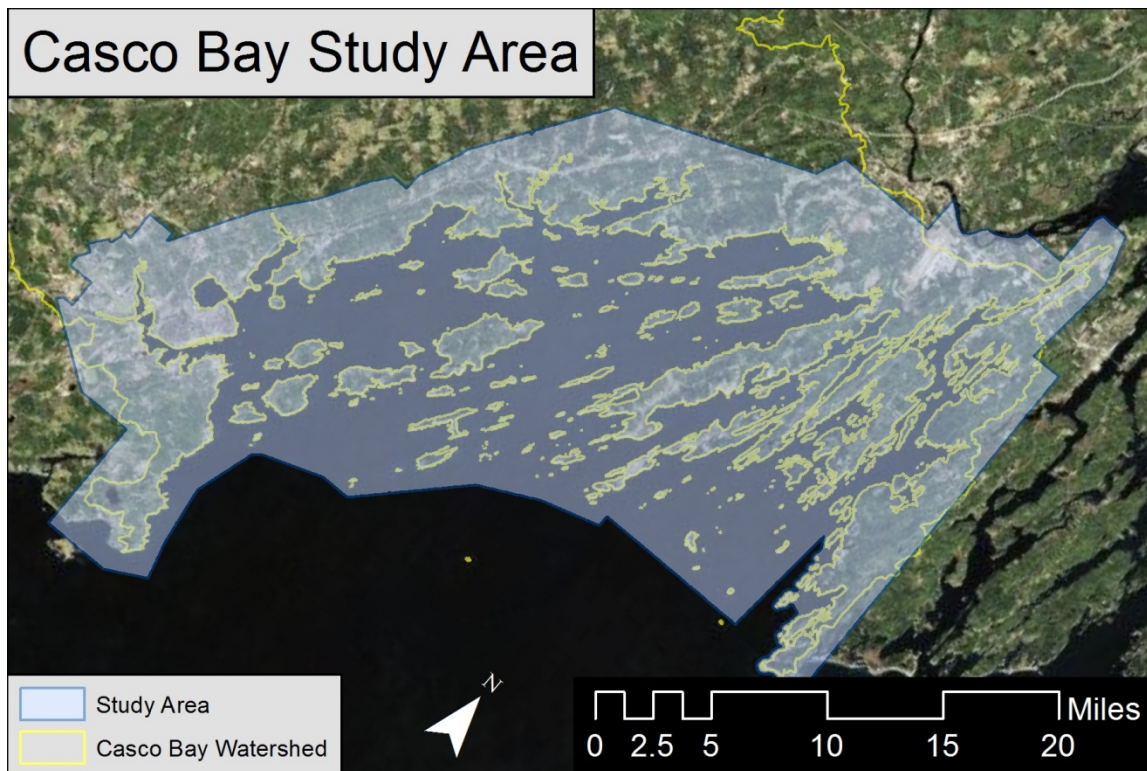


Figure 1: Boundaries of the Casco Bay Study Area (aerial photography from Bing, via ESRI).

Methods

Elevation Data from LIDAR

The study is based on a detailed analysis of high resolution elevation data derived from “LIDAR” technologies. LIDAR is technology similar to RADAR that uses light waves instead of radio waves to measure distance from a plane to the ground. Raw LIDAR data is post-processed to produce a “Digital Elevation Model” (DEM) that shows estimated ground elevations free of buildings, trees, and other obstructions. The resulting DEM can be highly accurate, with elevations estimated every few feet, absolute vertical errors typically less than a foot or so, and relative vertical errors often smaller than that on a local scale.

Two sources of LIDAR data were used in this analysis: (1) FEMA South Coast LIDAR 2006, (2) LIDAR for the Northeast 2011. Both data sets were acquired as DEM tiles from the University of Southern Maine’s Geographic Information Systems Laboratory in spring of 2011. LIDAR data covering most of the Casco Bay shoreline was acquired by FEMA in 2006. However, the 2006 data layer did not provide comprehensive coverage, with data gaps principally along the Phippsburg / Small Point shoreline and at the head of tidal inlets and embayments.

We supplemented the 2006 LIDAR data with selected tiles from the more recent “LIDAR for the Northeast 2011” dataset. The LIDAR for the Northeast data we received had already had marine waters “flattened” to an arbitrary constant elevation. This does not appear to have affected our analysis at most locations, but at one site (TR122, described below), data had been “flattened” over an extensive area of tidal marsh, making elevation-based analysis impossible. As received, the two data sets were based on different units of measure (feet vs. meters), so the LIDAR for the Northeast 2011 was scaled and resampled using bilinear interpolation³ before the two data sets were combined to produce a single composite LIDAR DEM for all of Casco Bay.⁴

Resampling the more recent data involves using the original DEM data, produced with a two meter pixel size (horizontal resolution) to estimate elevations that would be observed at pixels spaced at the smaller five foot pixel size consistent with the FEMA data. This process results in a minor loss of vertical resolution in comparison to the original data. In particular, the process of bilinear interpolation is essentially an averaging process, so the resampled data will end up flatter than the original data, on the scale of adjacent pixels. The process, however, has little effect on larger scale elevation patterns that were the focus of the current study.

Mosaicking the two LIDAR datasets to produce a single composite LIDAR coverage for Casco Bay affects the horizontal data accuracy at small scales. When two DEMs are combined, the point of origin of one or both DEMs must be shifted in east-west and north-south directions so that the two data sets can be combined seamlessly. ArcGIS documentation does not specify how this mosaicking process occurs, but the horizontal errors introduced should be under half a pixel width (2.5 feet). Our experience generating and regenerating LIDAR mosaics for this project shows that the particular sequence in which LIDAR tiles are mosaicked together affects the location of the origin of the final dataset.

³ All GIS analysis for this project was carried out using ArcGIS software (ESRI, Redlands, California). Arc “Models” were generated for all analytic steps, to document and automate procedures. Existence of the models facilitates data QA/QC, by permitting automated regeneration of data to check results and quickly repeat analyses in case problems are identified. Models separate the analytic procedures from site-specific data, and thus can be applied to data from other locations. Models are available from CBEP by request.

⁴ Casco_Bay_LiDAR_MOSAIC in the accompanying data distribution disk.

Location of the Upper Intertidal Zone based on Current Sea Level

LIDAR data was combined with information on tidal heights compiled by NOAA for the Portland tide gauge in order to identify portions of the shoreline that lie within the upper intertidal zone, between the Mean Tide Level or MTL and the Highest Astronomical Tide, (HAT).

These elevations are roughly coincident with the lower and upper limit of salt marsh development in Maine. As a first approximation, the transition between low marsh, dominated by salt marsh cordgrass (*Spartina alterniflora*) and high marsh, often dominated by salt meadow hay (*Sp. patens*) and blackgrass (*Juncus gerardii*), lies at or near the elevation of Mean High Water (MHW).

GIS analysis of the LIDAR data was used to produce “Current Sea Level” or “CSL” polygon data that identifies areas within the Casco Bay Study Area that lie at appropriate elevations for development of high and low marsh⁵.

Technical details

We estimated areas suitable for wetland development using a simple heuristic. Tidal marshes tend to occur along the Maine Coast between the elevations of MTL and HAT. Any area with elevations lying between these two levels has a high probability of producing tidal wetland. The division between low marsh and high marsh tends to occur close to the elevation of MHW.

Data on tidal datums for the Portland tide gauge were downloaded from NOAA’s website (see Table 2).⁶ All tidal elevations were referenced to North American Vertical Datum 1988 (NAVD), for compatibility with the LIDAR data. Datums are based on a Tidal Datum Analysis Period from 1983 through 2001. We used the elevations of the three key tidal datums (MTL, MHW, HAT) from the Portland tide gauge as cutoffs for generating projected wetland maps under current sea level (Table 3).

Even with these elevation cutoffs well defined, the process for generating polygon data from the LIDAR mosaic is somewhat complicated. The combination of a small (5 foot by 5 foot) pixel size and high digital precision (as opposed to accuracy) of the LIDAR data means that a simple “cut” of the LIDAR data by elevations produced highly convoluted areas. Such complex shapes do not reflect how wetlands develop on the landscape. Moreover, they are impractical to work with, as complex geometries require inordinate amounts of computer memory and processor time to manipulate. As a consequence, several techniques were used in GIS to produce data with a simpler geometry which better reflects the scale of patterns and processes in coastal wetlands.

⁵The current sea level polygon data is titled “CSL_Marshes_ONLY” in the accompanying data distribution disk. A version of the data which includes non-wetland elevations and clearly identifies areas where hand edits were necessary is also included, as “CSL_Edited”.

⁶ National Oceanic and Atmospheric Administration (NOAAA). 2012. Portland, ME, Station ID: 8418150. Data retrieval Datums: Data Inventory. http://tidesandcurrents.noaa.gov/data_menu.shtml?stn=8418150%20Portland,%20ME&type=Datums, Accessed July 9, 2012.

Table 2: Primary tidal datums for Portland, Maine, in feet. Datums are based on a Tidal Datum Analysis Period from 1983 through 2001, and thus reflect elevations a few inches below current levels. Sea levels at the Portland station have been rising approximately 0.7 inches per decade since the early 1900s⁷. Items in bold are the tidal datums used in this study to define cut-points in the LIDAR data and identify areas at appropriate elevations for development of tidal wetlands.

Tidal Datum	Abbreviation	Relative to Station Datum	NAVD
Highest Astronomical Tide	HAT	20.5	6.69
Mean Higher-High Water	MHHW	18.46	4.65
Mean High Water	MHW	18.02	4.21
Mean Diurnal Tide Level	DTL	13.51	-0.30
Mean Sea Level	MSL	13.49	-0.32
Mean Tide Level	MTL	13.46	-0.35
Mean Low Water	MLW	8.9	-4.91
Mean Lower-Low Water	MLLW	8.55	-5.26

Table 3: Elevation cutoffs used to identify areas suitable for tidal wetland development.

Interpretation	Range Relative to Tidal Datums	Elevation Range (ft. NAVD)	Elevation Code in GIS data
Marine Environments	Below MTL	$-\infty$ to -0.35	1
Low Marsh Elevations	MTL to MHW	-0.35 to 4.21	2
High Marsh Elevations	MHW to HAT	4.21 to 6.69	3
Upland and Non-tidal Wetland	HAT and above	6.69 to ∞	4

The process for generating polygon data was as follows (Figure 2 depicts steps 2 through 6 of this process):

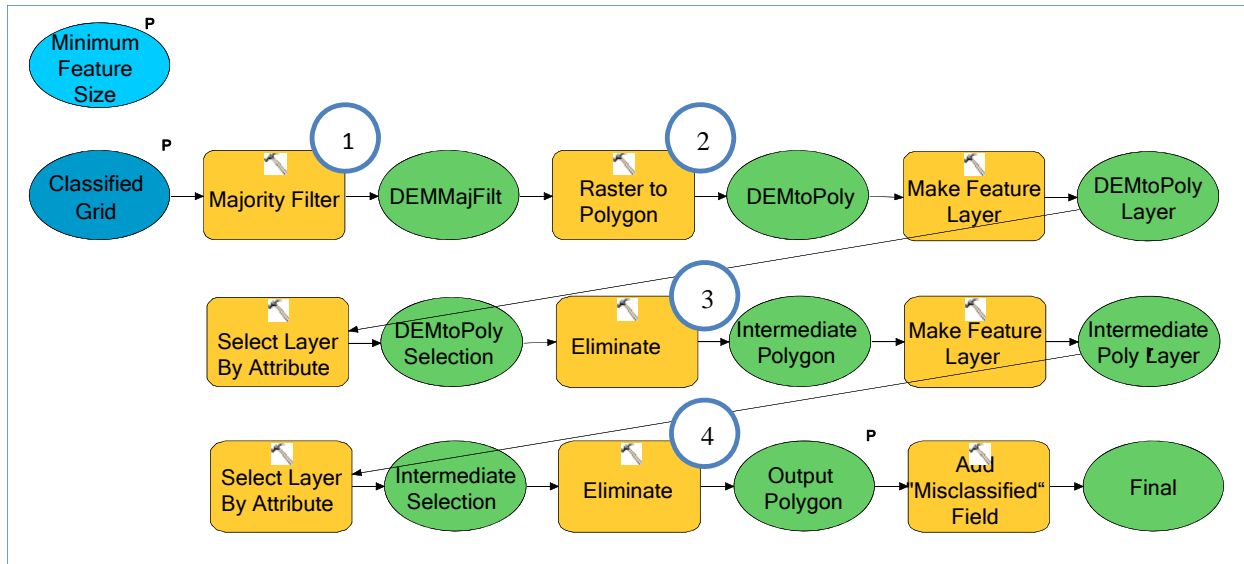
- (1) Reclassify the LIDAR data according to elevation, at the specific cut-points (third column of table 3), generating a draft GRID dataset coded by elevation category (last column of table 3).
- (2) Use a “majority filter” on the draft reclassified grid to merge isolated pixel in each elevation category with their neighbors. The Majority Filter was set to filter based on four (not eight) immediate neighbors of each pixel.
- (3) Convert the Grid to a polygon data layer, with the “Simplify Polygon” option turned on. The resulting polygon data layer retains a lot of small features, which are removed in the next two steps.
- (4) Select polygons less than 250 square feet, and “Eliminate” them by absorbing them into adjacent polygons with which they share the longest border.⁸

⁷ Wake *et al.* 2009, *Op.Cit.*

⁸ We tested several different size thresholds for the eliminate step, but could determine no compelling rationale for selecting a specific minimum size feature to use. We settled on 250 square feet because it represented about

- (5) Repeat step (4), to clean up additional small areas created in the previous step (not always necessary).
- (6) Add a data field to the Attribute table of the polygon data layer titled “Misclassified.”
- (7) Manually correct the data to account for classification and other errors. Rather than removing these areas from the data entirely we flagged them with the “Misclassified” data field. Errors were principally due to LIDAR data collected during moderate to high tides. Since the ocean surface lies within the upper intertidal zone at those times, significant areas of the marine environment were classified as above MTL. Most such areas were located away from the shore, and posed little problem. Where they did contact the shoreline, we delineated the boundary between marine and upper intertidal areas by hand based on aerial photography. A small number of other areas were also flagged as “Misclassified” in order to remove them from later analysis. These included areas covered by our LIDAR Mosaic that lie outside of Casco Bay (e.g., the tidal Androscoggin), a small number of rocky islets, and areas in and around Portland Harbor.⁹ Since all “Misclassified” polygons were retained in this data set, others can readily review the edits.
- (8) Export a “marshes only” version of the polygon data by selecting areas at wetland elevations that were not flagged as misclassified.¹⁰

Figure 2: Graphic depiction of steps in the ArcGIS Model used to produce polygon data from a Reclassified GRID. Key steps are (1) Majority Filter, (2) Raster to Polygon Conversion, (3) Select and Eliminate features under the Minimum Feature Size (250 sq. ft), and (4) Repeat the Eliminate step (required to eliminate small polygons missed or created in the first). Colors are from the Arc GIS Model Builder: Blue for input, orange for processes, green for results of analysis. The “Misclassified” field added in the last step was used to facilitate hand error correction and later processing.



10 pixels in the original LIDAR data, and the results gave an appropriate balance between simplicity and complexity.

⁹ These data are included in the data distribution disk as “CSL_Edited”.

¹⁰ “CSL_Marshes_ONLY” in the data distribution.

Testing Elevation-Based Wetland Maps

Because these data identify areas at elevations expected to support of present-day wetlands, they can be compared to other geographic and wetland data to evaluate how well they predict wetland areas. If elevation data alone does a relatively good job of predicting present-day wetlands, that increases confidence that predictions of future wetland areas may also be reasonable. We assessed how well these maps identify present-day wetlands using both quantitative and qualitative approaches.

Qualitative Comparisons

The Current Sea Level (CSL) maps were compared visually with wetland areas throughout Casco Bay where wetlands are known to occur. In particular, the data layer was compared to National Wetlands Inventory (NWI)¹¹ data and aerial photographs at dozens of wetland locations around Casco Bay.

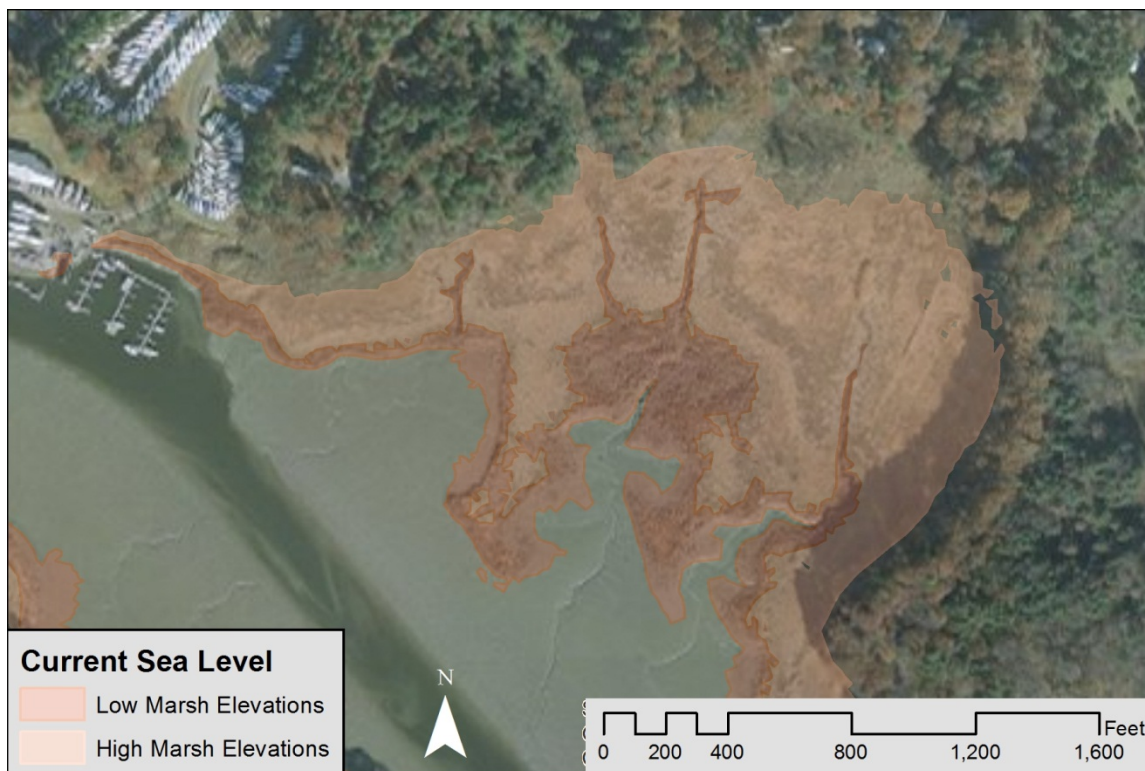


Figure 2: Example comparison of Current Sea Level (CSL) map data with aerial photography. At this site in the Royal River, the CSL wetland layer overestimates wetlands at the channel margin, and underestimates wetlands at the landward margin. The elevation data accurately predicts the boundary between low marsh and high marsh.

¹¹ Updated local National Wetlands Inventory Data was obtained from Robert Houston, at the U.S. Fish and Wildlife Service Gulf of Maine Coastal Program.

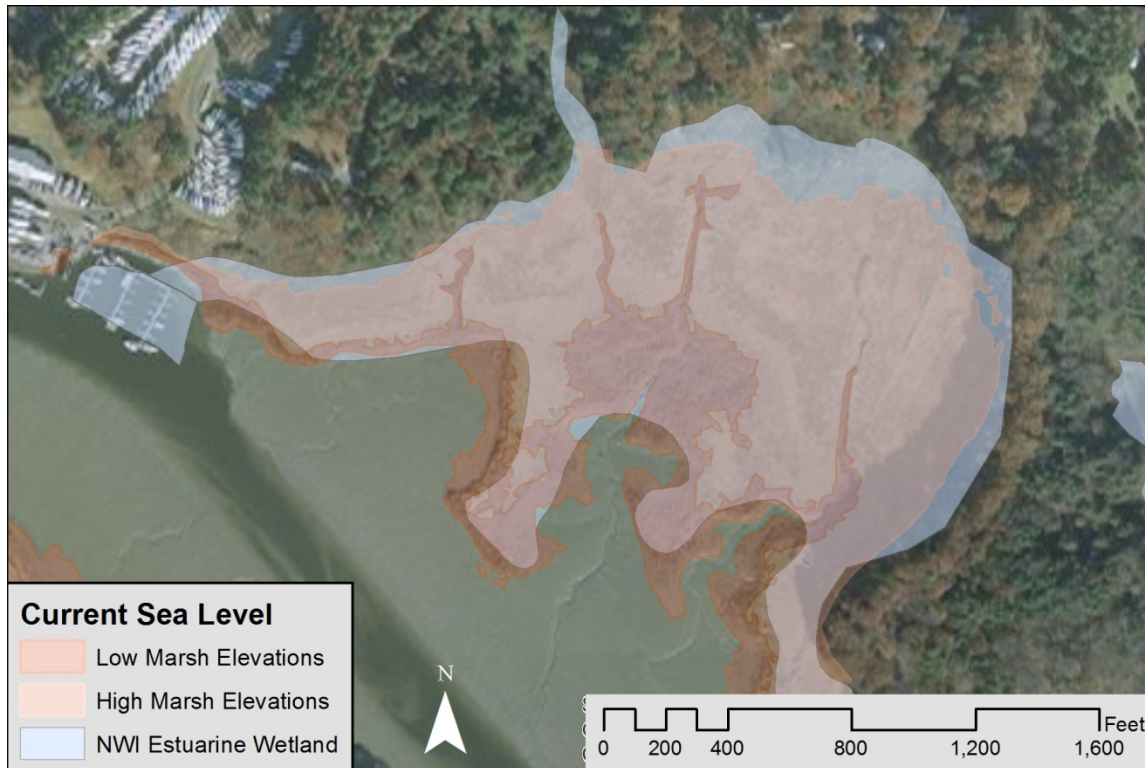


Figure 3: Example comparison of CSL data with NWI data. At this location, the correspondence is good, but not perfect. At this site the NWI boundaries do a better job than the elevation-based layers at picking up wetlands on the upland side of the wetland, but do not align well with wetland edge on the channel side.

The qualitative comparisons show that:

- (1) Agreement between the CSL data and other sources of information on wetlands is quite good at locations where wetlands occur. The elevation maps provide reasonable estimates of the upland and marine boundary of wetlands at most sites, and they do a credible job of predicting the boundary between high marsh and low marsh.
- (2) The elevation maps are slightly less successful at predicting the exact marine boundary of tidal wetlands. They sometimes overestimate the extent of vegetated wetland development at lower elevations, especially on exposed shores. Wave energy, erosion, and other processes not captured in elevation-based mapping appear to play a significant role in determining the marine boundary of tidal wetlands. LIDAR data from 2006, on which these polygons largely are based, would not reflect recent shoreline erosion.
- (3) As expected, significant areas are at appropriate elevation for development of tidal wetlands where tidal wetlands do not occur. Casco Bay has a lot of shoreline which is too steep, too rocky, or with too much wave exposure to support tidal wetlands.
- (4) In many cases, the elevation data does a better job of delineating wetland areas and distinguishing tidal from non-tidal wetland than does the National Wetlands Inventory, which was developed at a larger spatial scale from aerial photography.
- (5) Marsh vegetation (and NWI wetlands) sometimes extends above wetland elevations identified in these data, especially in areas with significant groundwater influx. The mismatch may reflect the presence of freshwater-dominated wetlands adjacent to tidal wetlands, or, ground elevation at these locations may be systematically overestimated due to poor LIDAR penetration through dense plant canopies.

Quantitative Comparison with Mapped Wetlands

The quantitative comparison of the CSL data with mapped wetlands was based on determination of geographic overlap between areas mapped as wetland, and areas in the CSL data that lie at wetland elevations. The CSL elevation maps were compared both to NWI data as well as to the higher resolution “Fringing Wetland” data released by CBEP in 2008.¹²

Two questions can be asked by such a comparison: (1) What proportion of areas mapped as estuarine or tidal wetlands are also at intertidal elevations (top row of tables on subsequent pages)?; and, (2) What proportion of areas at intertidal elevations are also mapped as estuarine or tidal wetland (first column of tables)?

Table 4: Comparison of CSL data with Estuarine Wetlands as mapped by the National Wetlands Inventory. “Estuarine” wetlands here are wetlands mapped under the NWI as part of the Estuarine System.¹³

		Tidal Wetland Elevations		
		Yes	No	Total
NWI Estuarine Wetlands	Mapped	59.2%	40.8%	100.0%
	Not Mapped	31.3%	--	
	Total	68.7%		100.0%

Table 5: Comparison of CSL data with tidal wetlands from the NWI. Tidal wetlands include all estuarine wetlands as well as wetlands with the “R,” “S,” “T,” and “V” hydrology modifiers.¹⁴

		Tidal Wetland Elevations		
		Yes	No	Total
NWI Tidal Wetlands	Mapped	42.7%	57.3%	100.0%
	Not Mapped	32.4%	--	
	Total	67.6%		100.0%

Despite qualitative agreement between CSL data and presence of wetlands, the quantitative comparison suggests caution. Only 59% of NWI estuarine wetland also fell within the wetland elevation ranges according to LIDAR. It appears (based on review of locations around Casco Bay), that this poor match primarily reflects

¹² Hayes, Peter, Rachel Carr, Michele Dionne. 2008. Project Report: Mapping and Restoration Inventory of Fringing Marsh Habitat in the Casco Bay Estuary. Available at http://www.cascobay.usm.maine.edu/habitat_fringing_marsh.html

¹³ Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U. S. Department of the Interior, Fish and Wildlife Service. Washington, D.C. FWS/OBS-79/31.

¹⁴ *Ibid.*

inaccuracies in the NWI maps. NWI wetland boundaries were drawn at a coarser spatial scale than the high resolution LIDAR data makes possible. Most NWI polygons mapped as tidal wetland include areas that clearly are not correctly classified, simply because of the coarse scale of the original NWI mapping. NWI data are based primarily on hydric soil information and interpretation of aerial photography. Certain classification errors are almost inevitable. Several locations shown in the NWI data as estuarine or tidal wetlands are in fact non-tidal wetlands adjacent to tidal waters, as can be ascertained by careful review of elevations. This situation is especially common on the Casco Bay islands.

Table 6: Comparison of CSL data with tidal wetlands from the region where CBEP’s “Fringing Marsh” data is also available. Restricting the comparison to the this region, which omits most Casco Bay islands, has little effect on the proportion of NWI mapped wetlands mapped by our techniques as at tidal wetland elevations, but it increases the proportion of the area at tidal wetland elevations that was mapped in the NWI.

		Tidal Wetland Elevations		Total
		Yes	No	
NWI Tidal Wetlands	Mapped	43.8%	56.2%	100.0%
	Not Mapped	41.2%	--	
	Total	58.8%		100.0%

Table 7: Comparison of CSL data with an expanded Tidal Wetlands data set. This data set includes areas mapped as tidal wetland either in the NWI or in CBEP’s “fringing marsh” data. The fringing marsh data mapped significantly smaller wetland features than the NWI. Addition of these data to the comparison further increased the proportion of the areas at tidal wetland elevations that were mapped as wetland in other wetland maps.

		Tidal Wetland Elevations		Total
		Yes	No	
NWI Tidal + Fringing Wetlands	Mapped	47.7%	52.3%	100.0%
	Not Mapped	49.0%	--	
	Total	51.0%		100.0%

The converse problem is more significant. Only about a third of the area located at elevations suitable for tidal wetlands across Casco Bay are mapped as tidal wetland under the NWI. That situation is improved slightly looking only at the mainland shore line (compare Tables 5 and 6) and by supplementing the NWI data with higher resolution data on fringing wetlands (compare Tables 6 and 7). Even with higher resolution wetland data, however, slightly more than half the area at suitable elevations is not shown as wetland in other geospatial data.

Even a quick review of the data shows why. Many areas at suitable elevations do not form wetlands at all, nor would they be expected to. They lie on exposed shorelines, or are rocky shores, steep bluffs, or beaches. While these shoreline features are relatively narrow, they form a majority of Casco Bay’s shoreline, so they add up.

Alternative GIS Model for Identifying Wetland Areas

Given the relatively poor performance at a regional scale of a simple elevation-based model, we explored approaches to distinguishing between wetland and non-wetland areas more effectively. Any approach useful in the context of sea level rise must be based on landscape characteristics that are observable today, and unlikely to change significantly. We considered three complementary approaches:

- (1) Most tidal marshes are relatively flat, so combining elevation and slope data might provide a way to distinguish wetland and non-wetland areas at intertidal elevations.
- (2) While fringing wetlands are common along Casco Bay, the preponderance of wetland area is located within larger wetland complexes. In contrast, most of the non-wetland area at intertidal elevations is found in long narrow ribbons along steep shorelines. Perhaps a geometric approach to identifying compact wetlands based on their perimeter to area ratios would help distinguish wetland from non-wetland.
- (3) Third, we had planned to test multiple regression techniques to predict the probability that a specific area at intertidal elevations, but have been unable to do so.

The most promising of these techniques are the elevation and slope models. Simple versions of these models reduce the area misclassified as wetland but they overlook substantial wetland area. Such models tends to omit fringing marshes, portions of wetlands adjacent to tidal creeks and portions of wetlands close to steep slopes. Better performance of these models should be possible by fine-tuning model parameters and GIS processing steps. Improved performance will likely be possible by adjusting (1) the scale at which to determine slope (pixel size), (2) the slope cutoff used to determine areas “flat enough” to be likely to be wetland, and (3) use of buffers around flat areas. The potential number of alternative models, however, becomes daunting. Finding optimal approaches will require exploring many tens of alternatives.

Table 8: Example comparison of an Elevation and Slope model with NWI data¹⁵. Compare to Table 4. Notice that a much higher proportion of the area identified as wetland in the Elevation and Slope model was mapped as wetland in the National Wetlands Inventory (77% as opposed to 31%). Conversely, the proportion of estuarine wetlands in the NWI not picked up in this model soared to more than ¾.

		Elevation and Slope Model		
		Mapped	Not Mapped	Total
NWI Estuarine Wetlands	Mapped	23.3%	76.7%	100.0%
	Not Mapped	76.8%	--	
	Total	23.2%		
		Total	100.0%	

¹⁵ The particular model evaluated here used a 25 foot pixel size to determine slope, considered sites with a slope under 3% to be low slope, and used no buffer.

Implications for Use of Elevation to Predict Wetlands Under Sea Level Rise

The bottom line is that elevation-based maps provide excellent indications of the boundaries of wetlands where they occur, but they also flag many areas that are not suitable for wetland development. As a consequence, elevation-based data are likely to provide good insight into wetland gains and losses at particular locations, but should be used with caution for assessing wetland gains and losses at a regional scale.

Location of the Upper Intertidal Zone Under Sea Level Rise

Data identifying areas where tidal marshes might be expected to occur under different sea level rise scenarios were generated using a simple “bathtub model”. In a bathtub model, future intertidal areas are identified by modeling a uniform increase in water levels, and identifying areas on the landscape at an elevation that would support tidal wetlands. Such models do not directly consider sediment accretion processes or possible complex responses of the tidal signal or local hydrology.

We produced polygon data for one foot (SLR 1 Ft), two foot (SLR 2 Ft), and three foot (SLR 3 Ft) sea level rise scenarios. Polygon data for the three sea level rise scenarios was produced the same way as the current sea level wetland maps, but with the relevant elevation cut-points increased by one, two, or three feet (see Table 8). Methods used to produce the polygon data for the three sea level rise scenarios were identical to those used to produce the CSL maps.¹⁶

Table 8. Elevation cut-points used to produce polygon data depicting areas at wetland elevations under sea level rise scenarios.

Interpretation	Range Relative to Predicted Tidal Datums	Elevation Range (ft. NAVD)				Elevation Code
		CSL	SLR 1 Ft	SLR 2 Ft	SLR 3 Ft	
Marine Environments	Below MTL	$-\infty$ to -0.35	$-\infty$ to 0.65	$-\infty$ to 1.65	$-\infty$ to 2.65	1
Low Marsh Elevations	MTL to MHW	-0.35 to 4.21	0.65 to 5.21	1.65 to 6.21	2.26 to 7.21	2
High Marsh Elevations	MHW to HAT	4.21 to 6.69	5.21 to 7.69	6.21 to 8.69	7.21 to 9.69	3
Upland and Non-tidal Wetland	HAT and above	6.69 to ∞	7.69 to ∞	8.69 to ∞	9.69 to ∞	4

¹⁶ Edited polygon data including all “Misclassified” polygons (“SLR_1ft_Edited”, “SLR_2ft_Edited”, “SLR_3ft_Edited”) and marsh polygon data (“SLR_1ft_Marshes_ONLY”, “SLR_2ft_Marshes_ONLY”, “SLR_3ft_Marshes_ONLY”) are included in the data distribution disk.

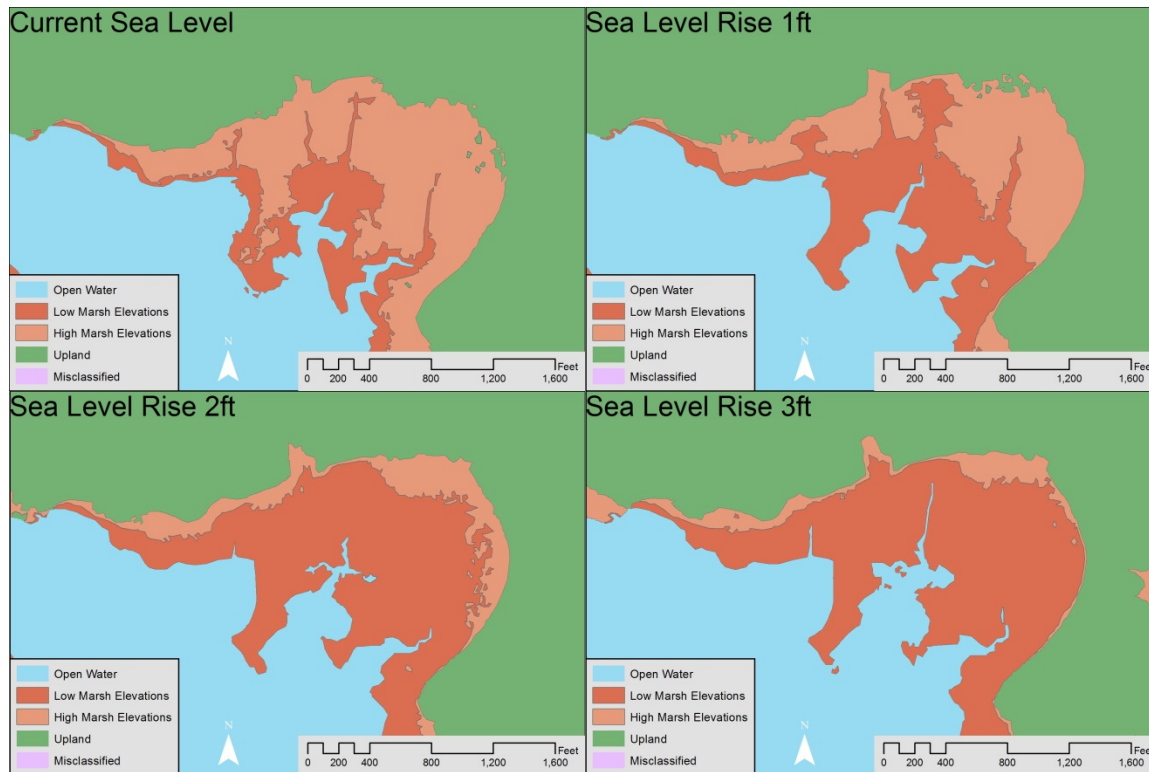


Figure 4. Example maps from the Royal River, showing effects of sea level rise on the area at intertidal elevations. At this site, wetland gains and wetland losses nearly balance, but a significant shift is projected to occur from a site dominated by high marsh to a site dominated by low marsh. This result is robust to reasonable assumptions about sediment accretion rates (see Part 2 of the report).

Wetland Gains and Losses

Map Data

For many planning purposes, maps that highlight change will prove more valuable than maps that show the extent of future wetlands. We combined data on areas at wetland elevations from current sea level and sea level rise scenarios to produce data that highlights areas of wetland gains and losses¹⁷.

Quantitative Estimates

One of the goals of this project was to develop quantitative estimates of the degree of wetland gains or losses across Casco Bay. However, the data we have generated to date, based only on wetland elevations, may be misleading for those purposes. As already discussed, the elevation-based wetland data layers we have produced include significant areas that do not support wetlands. We expect the data developed for each of the Sea Level Rise scenarios to do the same. That means a quantitative estimate of wetland gains and losses on a regional scale should await development of more refined analytic tools for predicting which areas at appropriate elevations will, and which will not, develop intertidal wetlands.

¹⁷ The wetland change layers are included in the data distribution disk as “SLR_1ft_Changes”, “SLR_2ft_Changes”, and “SLR_3ft_Changes”.

Nevertheless, we can produce an estimate of how the total area of the upper intertidal area around Casco Bay may change under each of the scenarios (See Figure 5). Projections suggest a large decline in the intertidal area at elevations suitable for development of high marsh (as much as a 37% decline), a more modest increase in areas at low marsh elevations (14%), and a slight decline in upper intertidal elevations overall (6% decline).

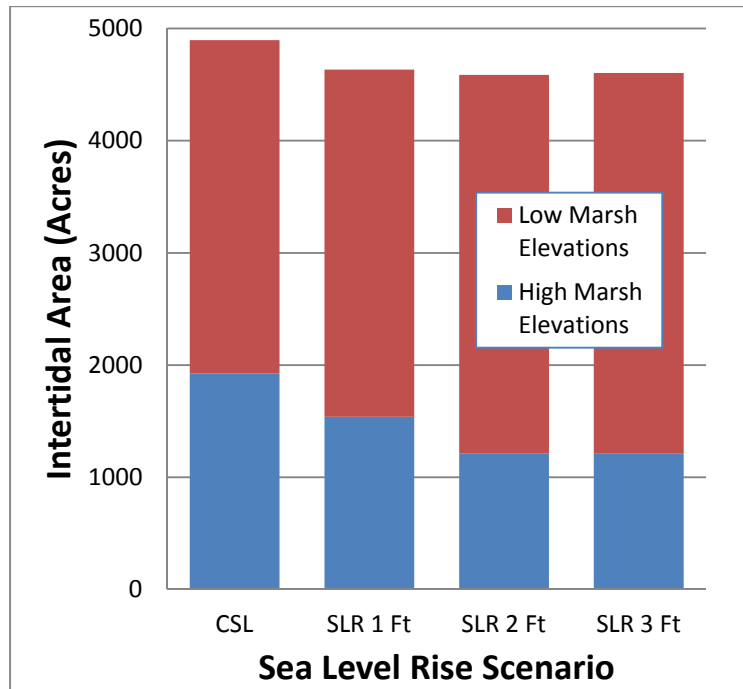


Figure 5. Total area within the upper intertidal zone under present conditions and three sea level rise scenarios. Because significant areas within the upper intertidal are not expected to develop intertidal wetlands, the figure should not be interpreted as depicting net change in wetland area. (Compare the pattern here, which suggests net loss of intertidal area with sea level rise, with estimates of wetland change at particular wetlands described in Part 2 and Part 3 of this report.).

Caveats

This simple approach used here to estimate location of wetlands based solely on elevation has three primary virtues. First, a bathtub model is a simple approach that is readily explained to stakeholders. The maps are valuable as illustrations of future tidal inundation, whether predictions about wetland behavior are correct or not. Second, the approach is relatively simple to implement in GIS. Third, it can readily be extended to generate maps of the locations of tidal wetlands under different sea level rise scenarios.

However, the method has a number of limitations. Technical users of the data we have produced should be aware of the data product’s limitations. First and foremost, not every location at these elevations support salt marshes today, and not every location that falls within these elevation ranges under different sea level rise scenarios will support tidal wetlands in the future. Salt marshes only occur where other environmental conditions are also suitable, such as having appropriate soils, low slopes and low to moderate wave

exposure. Many areas around Casco Bay lie at the appropriate elevations for tidal marsh development (e.g., beaches, exposed shores) but are obviously inappropriate locations marsh development.

Second, elevation relative to the Portland Tide Gauge is only an indirect indicator of whether suitable hydrology exists to support tidal marsh development, as explained below.

- (1) The processes that determine transition between wetland types are not driven directly by elevation. Elevation is a convenient proxy for other changes in the physical environment that shape wetland vegetation. In tidal wetlands, elevation acts principally as a surrogate for period of inundation, which itself influences edaphic properties like soil saturation, redox potential and nutrient concentrations in ways that directly affect vegetation.
- (2) While tidal elevations throughout the region are similar to what is observed at the Portland Tide Gauge, we know that tides vary across the region. NOAA publishes corrections to the tidal predictions for Portland so that mariners can predict timing and elevation of tides elsewhere in Casco Bay. For the open water sites of primary interest to boaters, however, differences are small. Tides in tidal estuaries and marshes are often quite different. Tides in tidal marshes (especially in Midcoast Maine's narrow head of valley wetland systems) often show delayed arrival of high tides, reduced tidal amplitudes, changes in high tide elevations, and low tides that are not as low as in adjacent open waters.
- (3) While geographically explicit modeling the hydrology and period of inundation of coastal wetlands is possible, it adds a level of complexity to analysis of the impact of sea level rise on tidal wetlands, and was considered beyond the scope of this project. Given the relatively small size of many Casco Bay wetlands, detailed modeling would be unlikely to alter the general findings of this study. Explicit modeling of tidal marsh hydrology should be considered, however, for detailed local studies.
- (4) In recent months, there has been increased attention to systematic bias in LIDAR-derived elevation data in tidal wetland habitats. Surface litter and dense plant canopies can block laser penetration to the ground surface, thus causing the LIDAR-derived elevation maps to overestimate elevation. This is an active area of research, and its significance for the current study is, for the time being, unknown.

Part 2: Sensitivity to Sediment Accretion Rates

We used GIS analysis of selected wetland sites around Casco Bay to study how the geomorphology of Casco Bay wetlands, sediment accretion rates, and sea level rise may interact to determine the fate of Casco Bay tidal wetlands in coming decades.

Sediment accretion rates are poorly constrained for many Maine wetlands. Only a handful of studies have directly measured sedimentation or accretion rates in wetlands in Maine or, more specifically, in Casco Bay.¹⁸ Broader patterns suggest that net accretion rates are positively correlated with tidal amplitude. In addition, the sediment dynamics of head of valley and fringing wetlands typical of the Casco Bay shoreline are complex, making deposition rates site specific and difficult to predict. While short term rates of sediment accretions in some Maine locations have been quite high, longer term accretion rates have primarily been in the range of about 1.5 to 4.5 mm per year.¹⁹ While these rates appear relatively modest, they translate into as much as 450 mm or about 17 inches of accretion in 100 years, certainly sufficient to affect the response of wetlands to rising seas. Historic rates may not be an especially good indication of accretion rates under more rapidly increasing sea levels, since accretion rates may be constrained by rates of sea level rise itself.

We used high resolution elevation data derived from LIDAR to model responses of wetlands in different geomorphic settings to three foot sea level rise. We developed a simple model to test how wetland response to rising seas may be affected by sediment accretion rates.

Site Selection and Classification

The geomorphology of the Casco Bay shoreline has a profound effect on the size, characteristics and spatial distribution of tidal marshes in the region. Wetlands along Casco Bay's steep shorelines and narrow, glacial cut embayments develop predominately in geomorphic settings classified by Kelley *et al.*²⁰ as fluvial-minor marshes, and bluff-toe marshes. A smaller number of sites along the tidal reaches of the Royal, Presumpscot, and Fore Rivers would be classified as fluvial-major marshes. A few Casco Bay wetlands are difficult to classify, appearing to be either intermediate between Kelley's categories, or examples of wetlands forming in less common geomorphic settings.

Direct application of Kelley's typology proved difficult based only on remotely sensed data, so we developed a closely related classification that could be more consistently applied for our purposes. We developed a heuristic classification of wetlands, in which we classified tidal wetlands into four geomorphic categories: "Head of Valley" wetlands, "Sheltered Fringing" marshes along larger tidal channels, "Exposed Fringing" wetlands on more open shorelines and "Other" wetlands.

Head of valley locations occur where tidal action extends into sheltered glacial and alluvial valleys. Sheltered fringing marshes are fringing wetlands where the maximum fetch (estimated as the maximum straight line distance to an opposite shore, omitting narrow lines along river channels) is less than 1,500 meters. They

¹⁸ Goodman, J. E., Wood, M. E., & Gehrels, W. R. (2007). A 17-year record of sediment accretion in the salt marshes of Maine. *Marine Geology* 242:109–121. doi:10.1016/j.margeo.2006.09.017.

Wood, M.E., J.T. Kelley, and D.F. Belknap, 1989. Patterns of sediment accumulation in the tidal marshes of Maine. *Estuaries* 12(4):237-2467.

¹⁹ Goodman *et al.* 2007. *Op. Cit.*

²⁰ Kelley, J.T., Belknap, D.F., Jacobson Jr., G.L., Jacobson, H.A. 1988. The morphology and origin of salt marshes along the glaciated coastline of Maine, USA. *J. Coast. Res.* 4, 649–665.

tend to be located on the banks of tidal rivers or between adjacent islands in eastern Casco Bay. Exposed fringing marshes are found in locations where maximum fetch is greater than 1,500 meters. Many form at the toe of eroding bluffs, or in sheltered microsites behind rocky ledges on otherwise exposed shores. The “other wetland “ category was used as a catchall for wetlands that appeared to be intermediate between other wetland types or were otherwise difficult to classify. Table 9 describes the relationship between our four classes and Kelley’s classification.

Table 9. Relationship between geomorphic categories used in our analysis and Kelley’s typology of Maine wetlands.

Geomorphic Settings Used in This Analysis	Most Common Kelley <i>et al.</i> 1988 Wetland Classification
Head of Valley Wetlands	Fluvial-minor marshes
Sheltered Fringing Wetlands	Bluff-toe and fluvial-major marshes
Exposed Fringing Wetlands	Bluff-toe marshes
Other	Mixture of difficult to classify sites, fluvial minor and bluff-toe wetlands

Random selection of tidal wetland sites proved to not be feasible because of the poor match between wetland elevations and presence of tidal wetland. Instead, the Casco Bay coastline between Cape Elizabeth and Phippsburg was examined to identify appropriate sites for analysis. Wetlands were selected to represent range of sizes and with the goal of finding a ten each of head of valley, sheltered fringing, and exposed fringing wetlands. NWI, Fringing Marsh, as well as the Current Sea Level and Sea Level Rise data layers described in Part 1 of this report were used to aid in locating areas of appropriate elevation for marsh under present conditions. The final sample consisted of ten Head of Valley sites, eight Sheltered Fringing Sites, twelve Exposed Fringing sites, and seven Other sites, for a total sample size of 37 wetlands (see Figure 6).

Once a potential site was selected based on the map data, aerial imagery was used to confirm whether marsh vegetation was present. Polygons were hand drawn in GIS delineating study areas surrounding the existing wetland and extending where possible from below -5 ft NAVD (below present-day upper intertidal elevations) to above 10 ft NAVD (above anticipated tidal inundation under three feet of sea level rise).

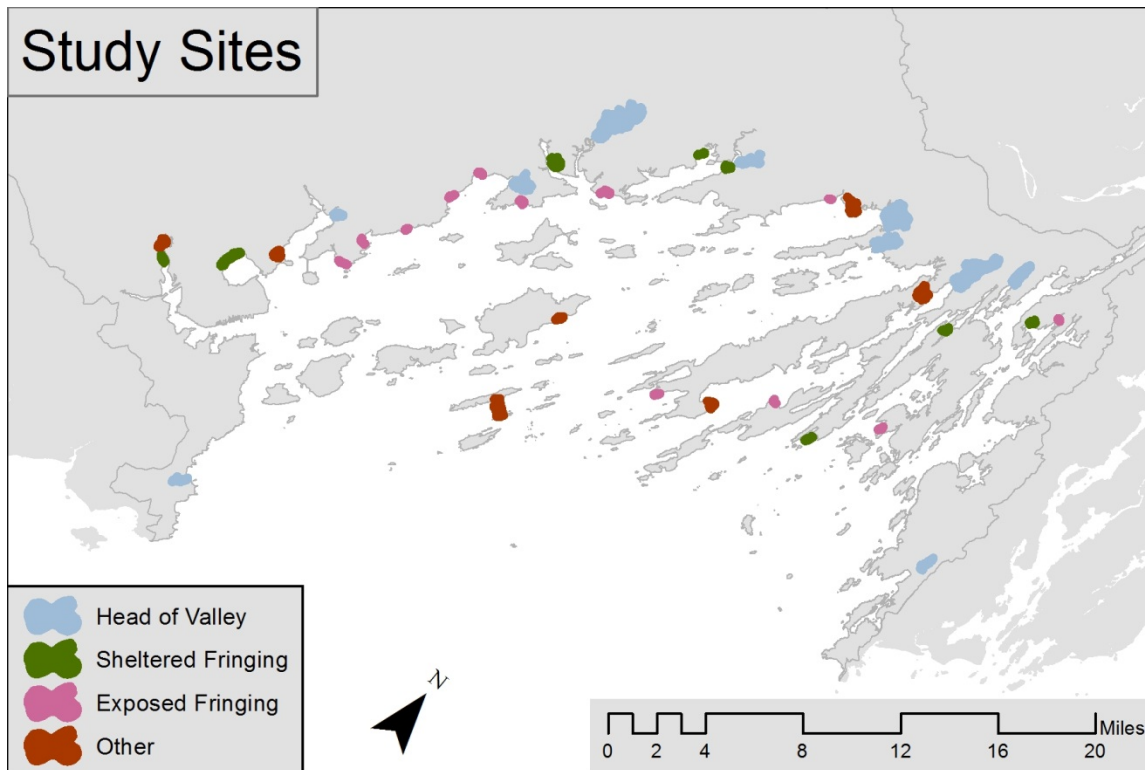


Figure 6. Location of the 37 study sites used to characterize response of Casco Bay wetlands to sea level rise.

Modeling Strategy

Wetland response to sea level rise was modeled for each site using a non-spatial model based on the hypsometric curve for each study area (the existing wetland and its adjacent uplands). A hypsometric curve is a curve that depicts the distribution of elevations within an area. We modeled changes in the hypsometric curve over time to predict future conditions at each of our study wetlands. Given the hypsometric curve and a specific sea level, one can readily calculate the area of tidal wetland predicted to occur.

Hypsometric Curve

The hypsometric curve for each site was derived in GIS in several steps. The LIDAR data for each study site was extracted from the Casco Bay LIDAR mosaic. The real-valued LIDAR data was converted to an integer-valued GRID with elevations measured in hundredths of feet. The attribute table for the integer-valued grid was then exported to excel, where elevations were converted back to feet and the area at each elevation was calculated based on the count of (5ft x 5ft) pixels at each elevation.

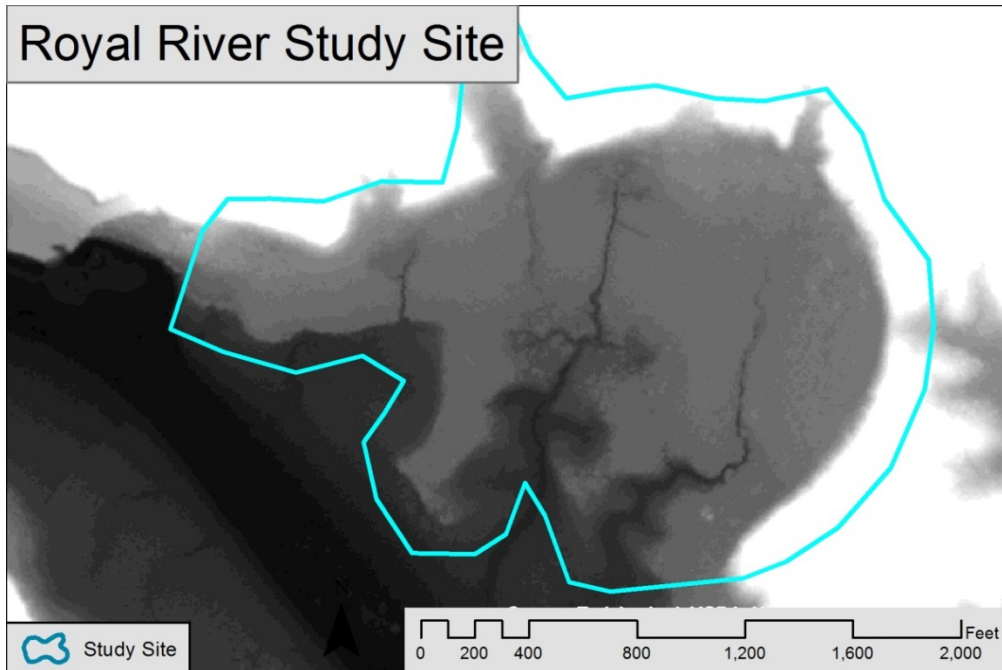


Figure 7. Selection polygon for Royal River study site, in Yarmouth, Maine, superimposed on LIDAR elevation data. The Royal River site is a Sheltered Fringing marsh, or a fluvial-major marsh under Kelley *et al.*'s classification.

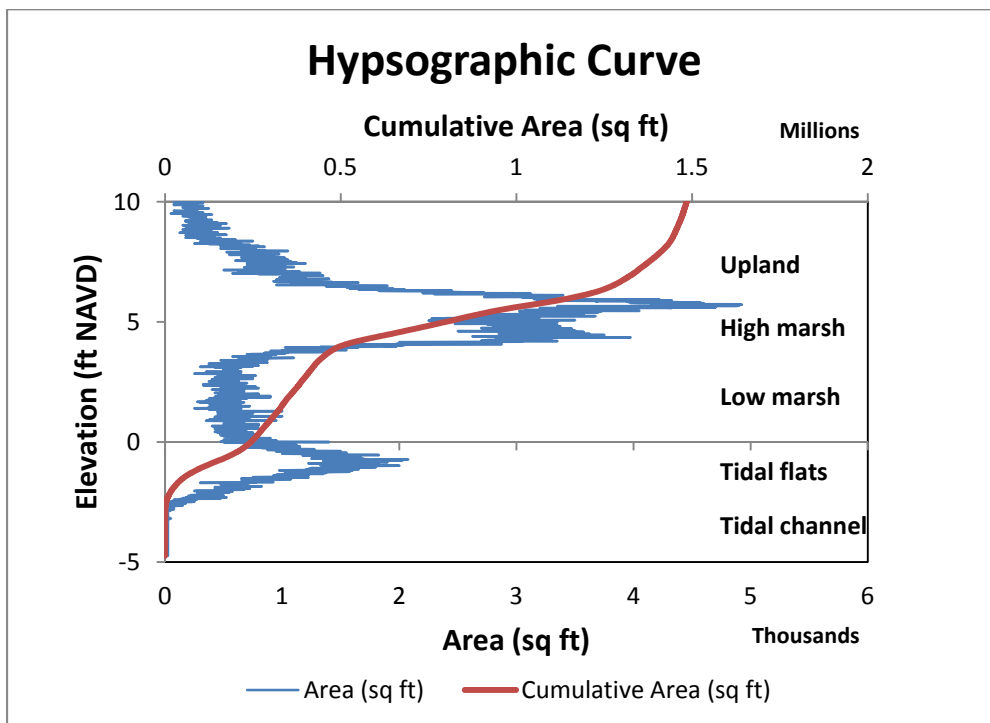


Figure 8. Hypsometric curve for the Royal River site,, showing large area close to and just above Mean High Water (4.39 ft NAVD). This high marsh shelf is a consistent feature of Casco Bay tidal wetlands.

Modeling Sediment Accretion

Sediment accretion processes were modeled for a three foot sea level rise over a 100 year period. The model used a five year timestep. Sediment accretion was modeled as a small increase in elevation at areas at intertidal elevations, based on predicted tidal heights at the start of each five year period.

Accretion was modeled as a piecewise linear function of depth of inundation (see Figure 9). The accretion rate is zero below tidal marsh elevations.²¹ Between MTL and an elevation specified by a parameter, the accretion rate equals the Maximum Accretion Rate (also set by a model parameter). Above the specified elevation, the accretion rate declines linearly to zero at HAT. For all model runs reported here, the elevation at which the accretion rate begins to decline was set to two feet above MHW.

We varied the Maximum Sediment Accretion Rate between 0 and 10 mm per year to study impact of different accretion rates on predicted wetland response to sea level rise.

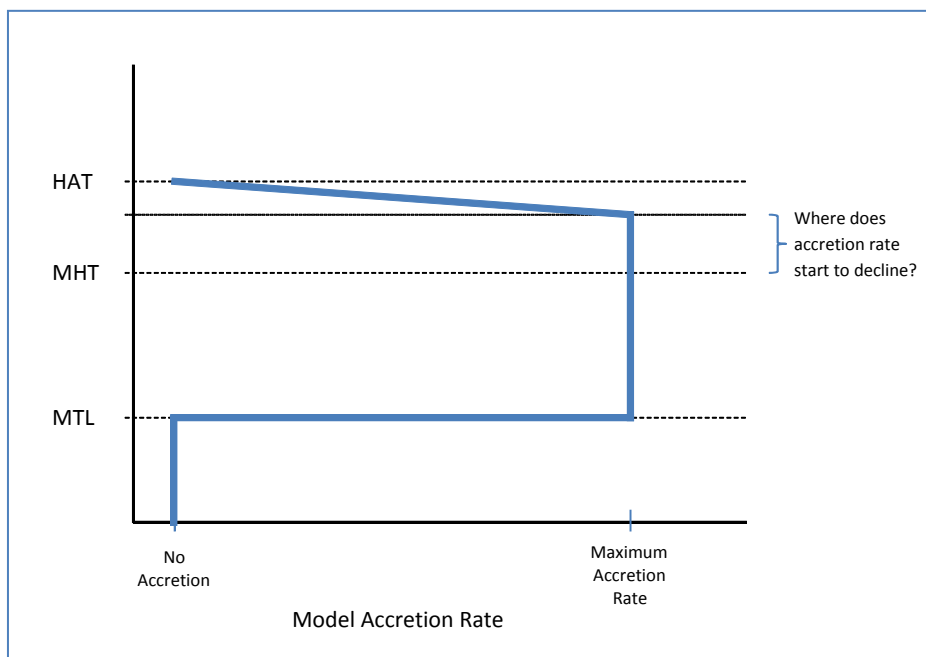


Figure 9. Graphic depiction of dependence of accretion rate used in the model as a function of (predicted) tidal inundation. Abbreviations refer to predicted tidal datums, and so change for each model time step.

For each five year time step in the model, a predicted increase in sea level was calculated based on a linear increase in sea level over the 100 year period. That increase in sea level was used to determine predicted elevations for key tidal datums. The sediment accretion model was then applied based on predicted tidal datums to increment elevations in the hypsographic curve. The result was predicted hypsographic curves for every five years over the model period (see figure 10).

²¹ Sediment accretion was modeled as zero below (predicted) MTL for simplicity. While that is not especially realistic, the area below MTL does not affect future predictions of wetland area, so this simplifying assumption has no bearing on model results.

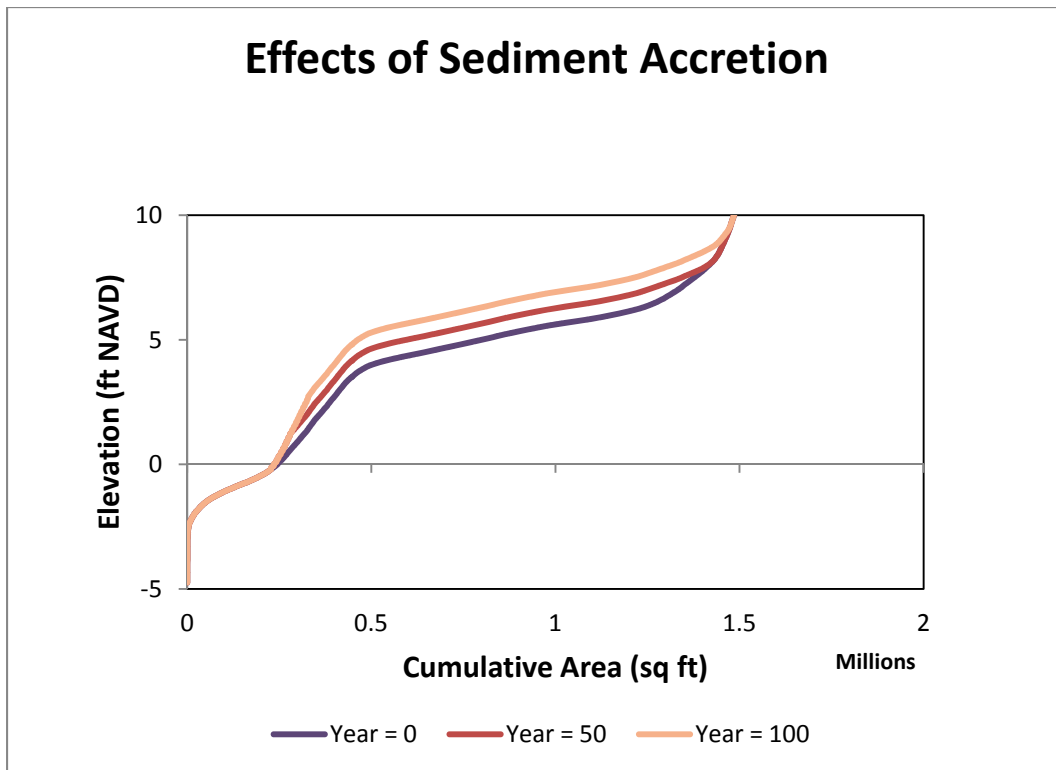


Figure 10: Effects of modeled sediment accretion on hypsography at the Royal River study site. These curves are based on a model with an accretion rate of 4 mm per year. Over a 100 year period, that adds up to 400 mm (almost 16 inches) total increase in elevation in parts of the marsh.

With estimates of the hypsography of wetlands in the future, it is a simple matter to apply “bathtub model” logic to estimate future wetland area based on predicted tidal datums under sea level rise. Results for the Royal River study area with a sediment accretion rate of 4mm per year are shown in Figure 11.

Results

Data Analysis

We ran our model for each of the thirty seven sites we identified around Casco Bay. We examined the response of wetlands under 3 ft. of sea level rise and 100 years of simulated sediment accretion.

Study wetlands varied by more than two orders of magnitude in area, from about half an acre to over 125 acres. Our interest focused on the RELATIVE change in area of wetlands, rather than ABSOLUTE change in area. As a result, we analyzed model results in terms of three response variables: (1) relative wetland area, (2) relative high marsh area, and (3) relative low marsh area. All three measures were calculated by scaling model results by present day wetland area:

- Relative Wetland Area (RA) $RA = \frac{A}{IA}$
- Relative Low Marsh Area (RL) $RL = \frac{L}{IA}$
- Relative High Marsh Area (RH) $RH = \frac{H}{IA}$

Where:

A = Model prediction of total wetland area (low marsh elevations plus high marsh elevations) at year 100.

L = Model prediction of low marsh area at year 100.

H = model prediction of high marsh area at year 100.

IA = Initial wetland area. Low marsh elevation plus high marsh elevations observed today.

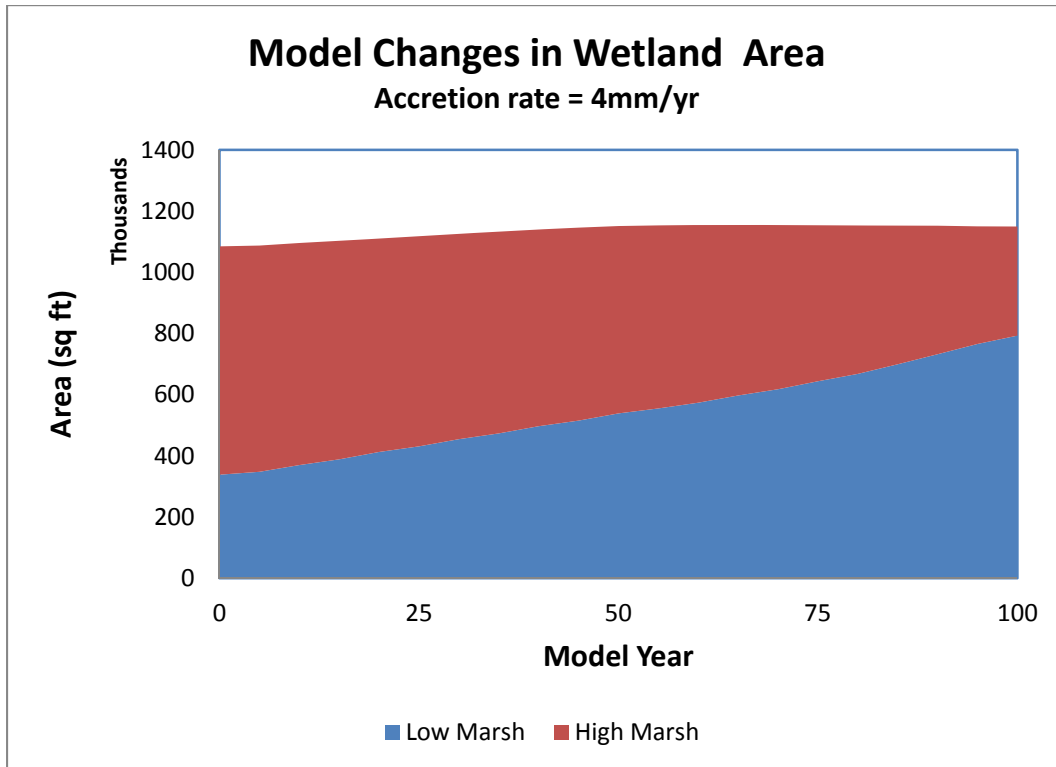


Figure 10: Modeled changes in high marsh and low marsh area over time at the Royal River study site. The graph is additive, so the top of the red area shows net increase in wetland area. Shown are model results with three foot (0.91 m) sea level rise and sediment accretion rates of 4mm (0.15 inches) per year. Overall wetland area at this site is predicted to increase, but with a significant conversion of high marsh to low marsh over time.

Graphical Summary

Results for individual sites are highly variable. For example, predictions for changes in total wetland with an accretion rate of 4mm per year ranged from a net loss of 42% of wetland area over 100 years to a net gain of 820%.

This wide range of response posed statistical challenges, since use of conventional least squares regression techniques on “heavy tailed” data such as these can be misleading. We resorted to using robust statistical methods to characterize the response of different wetlands to sea level rise. Robust statistical methods are a family of techniques designed to work more efficiently with data like these with heavy tailed error

distributions.²² In effect, these methods pay less attention to large deviations from model predictions than do conventional least squares techniques. Results are less influenced by a small number of unusual responses and thus provide a better summary of the majority of the data.

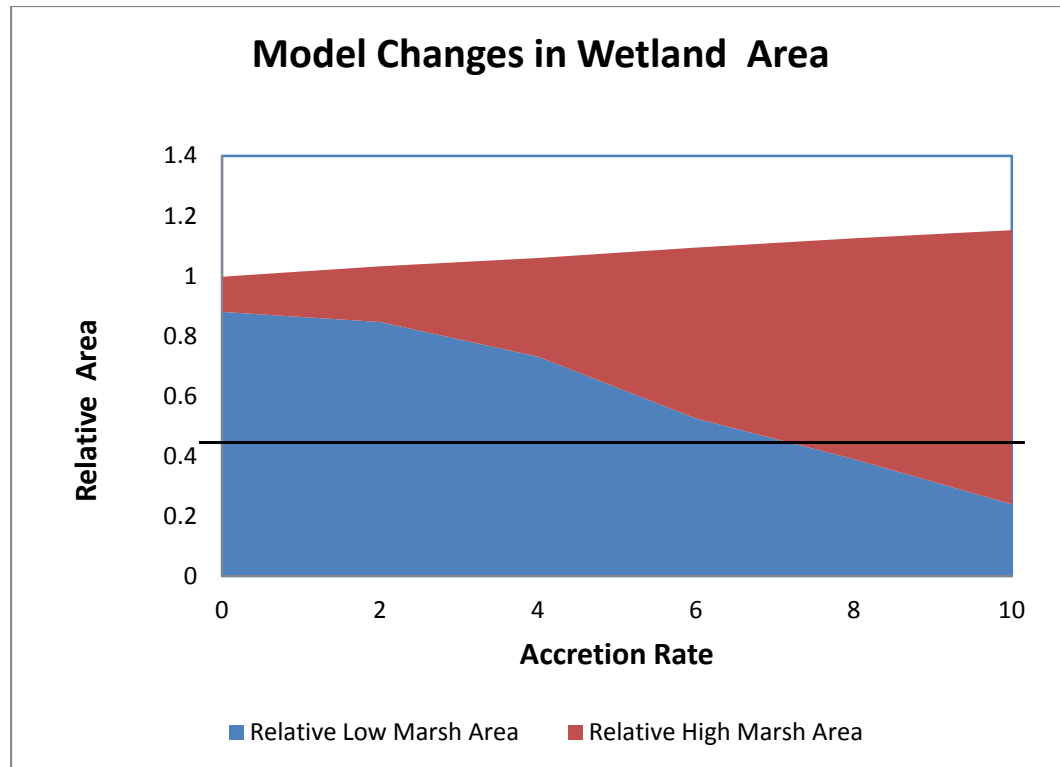


Figure 11: Modeled changes in high marsh and low marsh area as a function of accretion rate at the Royal River Study site. The graph is additive, so the top of the red area shows net increase in wetland area. Shown are model results with three foot (0.91 m) sea level rise. At this site, almost no change in wetland area is predicted in the absence of sediment accretion, but wetland gains increase with accretion. At low accretion rates, the model predicts a significant shift from high marsh to low marsh. The black reference line shows the proportion of the marsh in low marsh today, at about 45%.

Figure 12 shows a graphical summary of model results for all wetland sites. At low accretion rates, fringing marshes generally lose wetland area, but head of valley wetlands and the catchall “Other” category mostly gain. All wetlands lose high marsh and all but exposed fringing marshes gain low marsh at low accretion rates. Accretion rates have to be quite substantial to avoid relative loss of high marsh.

²² Wilcox, R. R. (2005). Introduction to Robust Estimation and Hypothesis Testing (Second Edition). Elsevier Academic Press, London.

Change In Wetland Composition

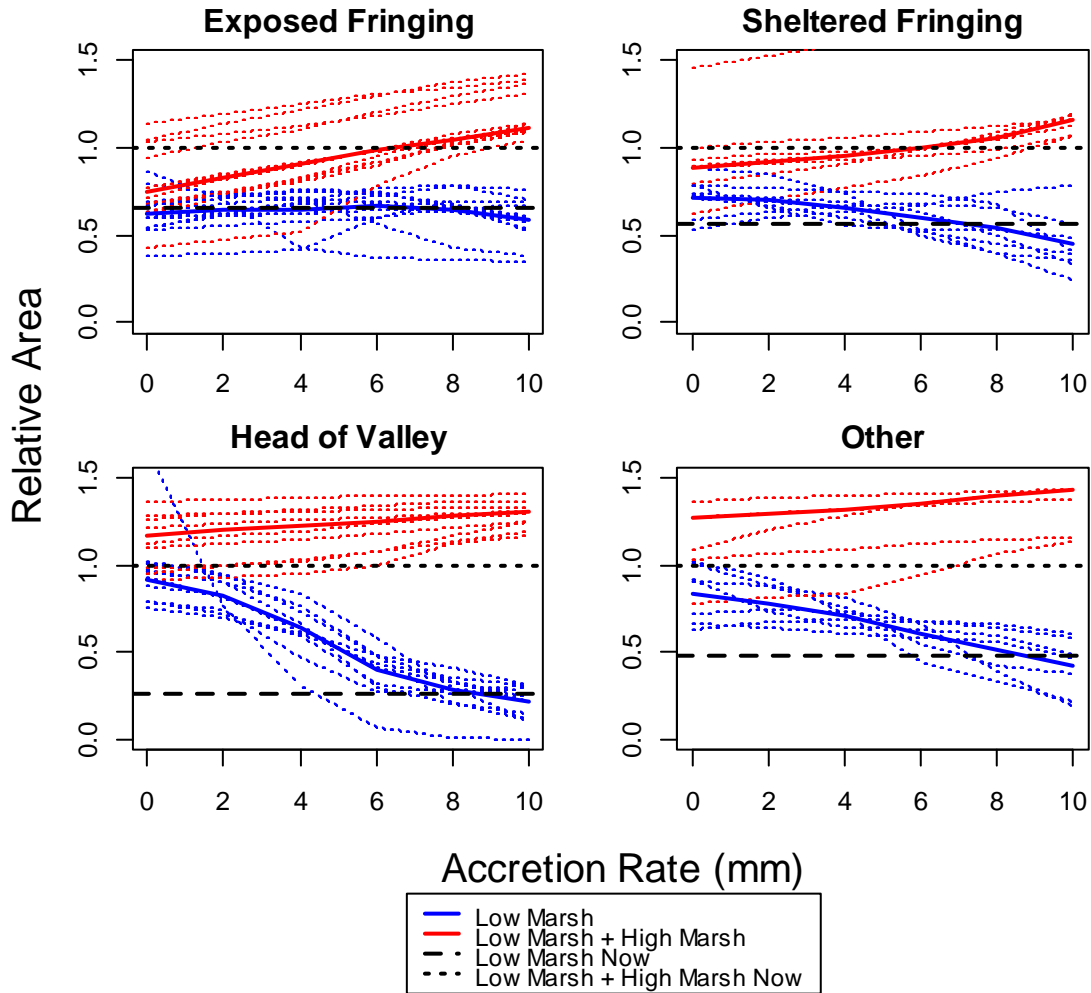


Figure 12: Graphical summary of model results. Graphic is designed to be reminiscent of the area plot in Figure 10. Areas below the blue lines indicate the effects of sea level rise on low marsh, and the red lines indicate the combined effects on low and high marsh. The effects on high marsh alone are shown by the gap between the red and blue lines. Thin dotted lines are drawn through responses from individual study sites. The heavy solid lines are drawn through the 10% trimmed means of the response for all wetlands. The trimmed means technique omit the 10% most extreme values and then calculate an average in the usual way. In this case, with small sample sizes, these values omit the single most extreme observation only. Dashed horizontal lines are for reference with present-day conditions. Vertical scale has been shortened to highlight patterns. Responses of some wetlands are not visible on the plots.

Statistical models

The robust methods used for these analyses are implemented in the statistical package “R”²³ in particular using the “rlm()” (Robust Linear Model) function available as part of the “MASS” package, released to accompany Venables and Ripley 2002.²⁴ By default, this function uses Huber’s M estimator with tuning parameter $c = 1.345$. We explored alternative estimators, including the robust resistant MM estimators, but they offered little advantage over the default method.

Robust methods pose some problems for determining statistical significance; however, our focus here was on estimation of parameters to summarize wetland response. We evaluated statistical significance of individual regression coefficients using “t” tests based on the ratio of estimates of parameter values and standard errors, but the models we have used do not account for correlated errors in the data²⁵, and thus standard errors and significance levels should be viewed very skeptically. More accurate standard errors and significance tests would require use of bootstrap techniques.

Quantitative results of the analysis are presented as regression equations in Tables 10 through 12. Results for our two different “fringing” marsh wetland categories are very similar. Models that consider only two wetland categories, “Fringing” and “Non-Fringing” explain nearly as much of the pattern in our model results as does the full model with all four wetland categories. Otherwise, the findings of the quantitative analysis mirror interpretation of the graphical summary of the data.

Table 10. Robust regression equations for relative wetland area (RA). Equations are derived from a single multiple regression model, with parameters derived for each of the four wetland types broken out here for convenience. Numbers in parentheses represent the standard errors for parameter estimates, but these standard errors do not yet fully account for correlated errors. Standard errors should not be trusted.

Wetland Category	Robust Regression Equation
Exposed Fringing	RA = 0.7778 (0.041) + 0.8773 (0.0502) * (Accretion Rate)
Head of Valley	RA = 1.1536 (0.0449) + 0.0413 (0.0068) * (Accretion Rate)
Other	RA = 1.2539 (0.0537) + 0.0149 (0.0074) * (Accretion Rate)
Sheltered Fringing	RA = 0.8773 (0.0502) + 0.0172 (0.0089) * (Accretion Rate)
Residual standard error: 0.1589 on 214 degrees of freedom	

²³ R Core Team (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org/>. Version 2.15.1 (released 06-22-2012.)

²⁴ Venables, W. N., B., & Ripley, D. (2002). Modern Applied Statistics with S (Fourth Edi., p. 495). Springer. New York.

²⁵For each study site, modeled responses at each accretion rate are correlated. Strictly speaking, the results should be analyzed with a hierarchical mixed model, in which each wetland is treated as a random factor in the model. We have not been able to find software designed to handle hierarchical models in a robust regression framework.

Table 11. Robust regression equations for relative low marsh area (RL). Caveats as in Table 10.

Wetland Category	Robust Regression Equation
Exposed Fringing	$RL = 0.6427 (0.0254) + 0.7545 (0.0311) * (\text{Accretion Rate})$
Head of Valley	$RL = 0.9370 (0.0278) + -0.0010 (0.0042) * (\text{Accretion Rate})$
Other	$RL = 0.8631 (0.0332) + -0.0773 (0.0046) * (\text{Accretion Rate})$
Sheltered Fringing	$RL = 0.7545 (0.0311) + -0.0416 (0.0055) * (\text{Accretion Rate})$
Residual standard error: 0.09463 on 214 degrees of freedom	

Table 12. Robust regression equations for relative high marsh area (RH). Caveats as in Table 10.

Wetland Category	Robust Regression Equation
Exposed Fringing	$RH = 0.1419 (0.0422) + 0.1221 (0.0516) * (\text{Accretion Rate})$
Head of Valley	$RH = 0.2211 (0.0462) + 0.0391 (0.0070) * (\text{Accretion Rate})$
Other	$RH = 0.3204 (0.0552) + 0.0898 (0.0076) * (\text{Accretion Rate})$
Sheltered Fringing	$RH = 0.1221 (0.0516) + 0.0756 (0.0091) * (\text{Accretion Rate})$
Residual standard error: 0.1661 on 214 degrees of freedom	

Discussion

Wetland response to sea level rise falls into two categories: (1) “Head of Valley” and “Other” wetlands show significant increases in wetland area under sea level rise. (2) In contrast, “Sheltered fringing” and “Exposed Fringing” wetlands are predicted to decline in area at low to moderate sediment accretion rates. Fringing wetlands are predicted to increase only for higher accretion rates, over about 5mm per year.

While sediment accretion rates of 5 mm per year have been observed in Maine, they are not common. Going on past sediment accretion rates, therefore, we should expect significant loss in fringing marshes in Casco Bay. However, almost all of our “Fringing” wetlands belong to Kelley *et al.*'s “bluff-toe” wetland category. These wetlands are hypothesized to persist due to a dynamic balance between erosive loss of wetland sediments and delivery of sediments from eroding bluffs.²⁶ It is reasonable to suspect that rising seas will lead to increased erosion on many coastal bluffs, increasing sediment delivery to fringing wetlands. Inundation is likely to alter wetland vegetation and thus affect organic matter deposition, decomposition and retention of sediments by plants. At present it is impossible to predict the combined effects of inundation, vegetation change, and increased bluff erosion on wetland sediments. Fringing marshes in Casco Bay are at risk due to sea level rise, but the degree of threat is not clear. Additional study is needed in understanding the effects of rising seas on bluff-toe wetlands in Maine.

²⁶ Kelley et al. 1988. Op. Cit.

Our model results suggest that all Casco Bay wetlands will undergo a change in character in the next century, from high-marsh dominated today, to low-marsh dominated in the future. The degree of transition from high marsh to low marsh will largely be determined by the relative rates of sediment accretion and sea level rise. These predictions are largely driven by the high fraction of Casco Bay's intertidal wetlands that lie at elevations at or just above Mean High Water. These high marsh flats, the result of more than 4,000 years of gradually rising seas, place a large fraction of the regions tidal wetland area just a few inches above MHW, where a relatively modest excess of sea level rise over sediment accretion would lead to changes in wetland character over time.

Head of Valley wetlands are complex estuarine environments, where sediment delivery from both upland and marine sources occurs. Each wetland is uniquely situated with regards to the relative importance of upland and marine materials. Detailed studies of sediment composition and sediment dynamics are needed in a representative collection of these systems to develop quantitative and semi-quantitative models of sediment dynamics to help develop site-specific understanding of wetland change over time.

Many areas in Head of Valley wetland complexes where tidal wetland may migrate in future support non-tidal wetlands today. This makes evaluation of the long term effects of sea level rise more complicated. The boundary between tidal and non-tidal and between freshwater, brackish and salt marshes will be determined dynamically by the hydrology of individual wetland valleys. Increased sea levels will both increase salt intrusion into these wetland systems, and also raise groundwater elevations, altering the boundaries and locations of freshwater wetlands. Introduction of sea-water derived sulfates into freshwater systems may increase decomposition of soil organic matter, lowering ground surface elevations and releasing stored CO₂. The dynamics of this process are little understood.

Part 3: Using LIDAR to Evaluate Restoration Opportunities

Introduction

Casco Bay Estuary Partnership maintains a running list of potential tidal restoration sites around Casco Bay. A majority of sites on the list were first identified through the “Return the Tides” project in the late 1990s. Additional sites have been identified via interpretation of aerial photography, field reconnaissance, and communication with local officials. Currently CBEP has a list of about 128 known or possible tidal restrictions affecting salt marshes and intertidal habitats around Casco Bay.

In 2012, CBEP began a project to develop methods to prioritize restoration among these 128 sites. As part of that project, we developed desktop and field reconnaissance methods to gather information that would help evaluate potential ecological benefits of tidal restoration, characterize significant challenges to restoration projects, and gather information needed to evaluate project costs. Here we report on efforts to use LIDAR to help inform that process.

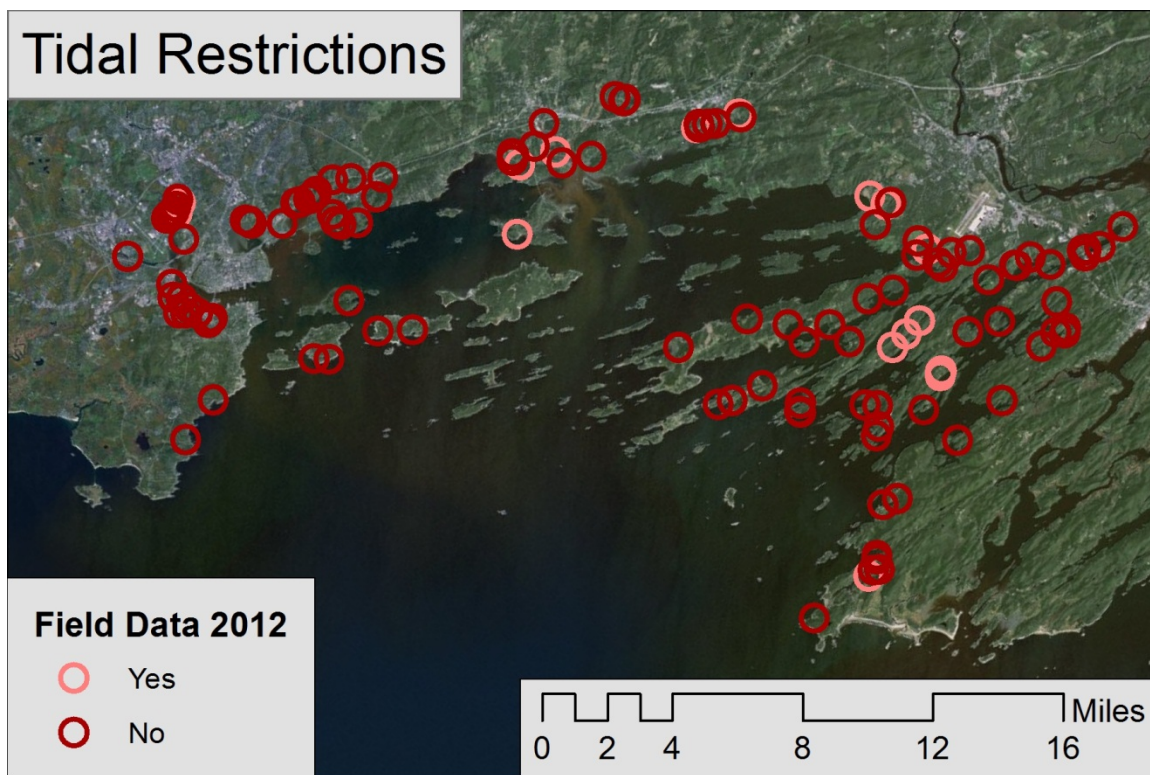


Figure 13: Map of 128 candidate tidal restriction restoration sites. Comprehensive field data was collected by field crews in 2012 at the sites with pink symbols.

Field crews in 2012 visited more than 30 tidal restriction sites, and collected comprehensive data, including relative upstream and downstream elevations on 20 sites. Field crews collected data on numerous parameters, including structural assessments, relative marsh surface elevations, stream cross sections, longitudinal channel and marsh profiles and vegetation. Desktop analysis included evaluation of site size,

identification of neighboring landowners, and assessment of degree of development adjacent to the site. Detailed hydrologic monitoring was collected at selected sites using pressure-conductivity data loggers.

Much of the data collected has not yet been fully analyzed, but preliminary findings have shown:

- (1) Diversity of tidal restrictions around Casco Bay is greater than imagined. Restrictions at many sites do not correspond to the classic model of a road crossing a tidal marsh at intertidal elevations. Dams at the head of tidal wetlands are far more numerous than we had thought. Sites where the character of the wetland changes sharply at the restriction are numerous – but it can be difficult to determine whether the restriction is a cause of that change, or if the structure was built at the natural head of tide or a break in slope.
- (2) Detailed field reconnaissance of these sites is time consuming and expensive. Even accessing a site can take days of planning. Data collection requires two people in the field, and each site generally takes at least a day. Vagaries of field work mean return visits are frequent.
- (3) Improved methods for screening sites would reduce costs of site evaluation.

Use of Longitudinal Profiles to Evaluate Restoration Sites

Most tidal restrictions occur where roads or other linear structures cross tidal inlets of head of valley tidal wetlands. We tested use of longitudinal profiles derived from LIDAR as a screening tool to evaluate candidate tidal restriction sites. For each of the 128 sites in the list of candidate sites, we drew a single line down the length of the tidal valley, extending (where possible) from above 10 ft. NAVD to below -5 ft. NAVD. We used aerial photography and LIDAR data to help guide us in drawing a profile down the tidal valley that followed valley meanders but did not follow tidal channels.

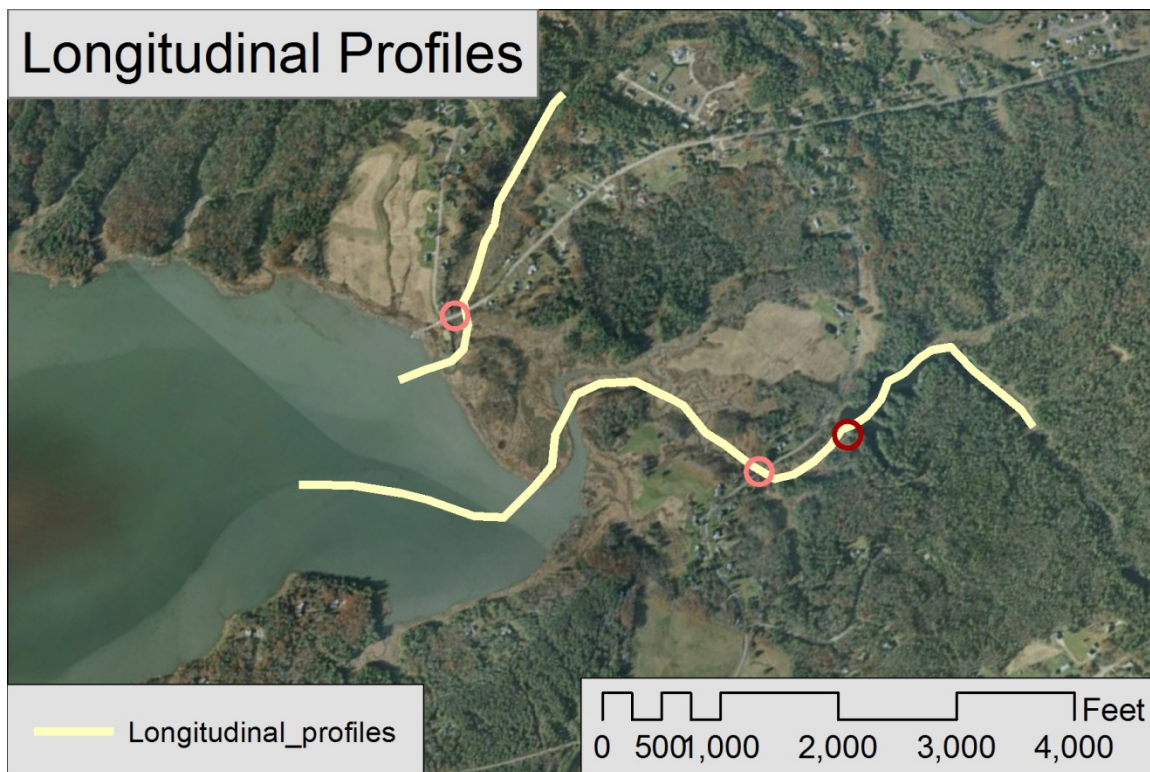


Figure 14. Example of two longitudinal profiles drawn through three candidate tidal restrictions at the head of Maquoit Bay, sites TR62, TR63, and TR64.

Using GIS, we extracted the elevations under these lines²⁷, with a typical spacing between successive elevations of approximately 5 feet.²⁸ We exported the resulting data, which includes distance and elevation information, to the statistical package “R”.²⁹ In R, we developed custom functions to extract the information, generate a robust linear regression fit for changes in elevation along the line, and graph the resulting information. The user can choose to include horizontal reference lines on the plot related to present or future tidal datums.³⁰

Derivation of the robust fit slope line for each profile occurs as follows: (1) the function calculates local maximum elevations, with a spacing determined by a “Window” parameter. A robust linear regression is fit through those local maxima.

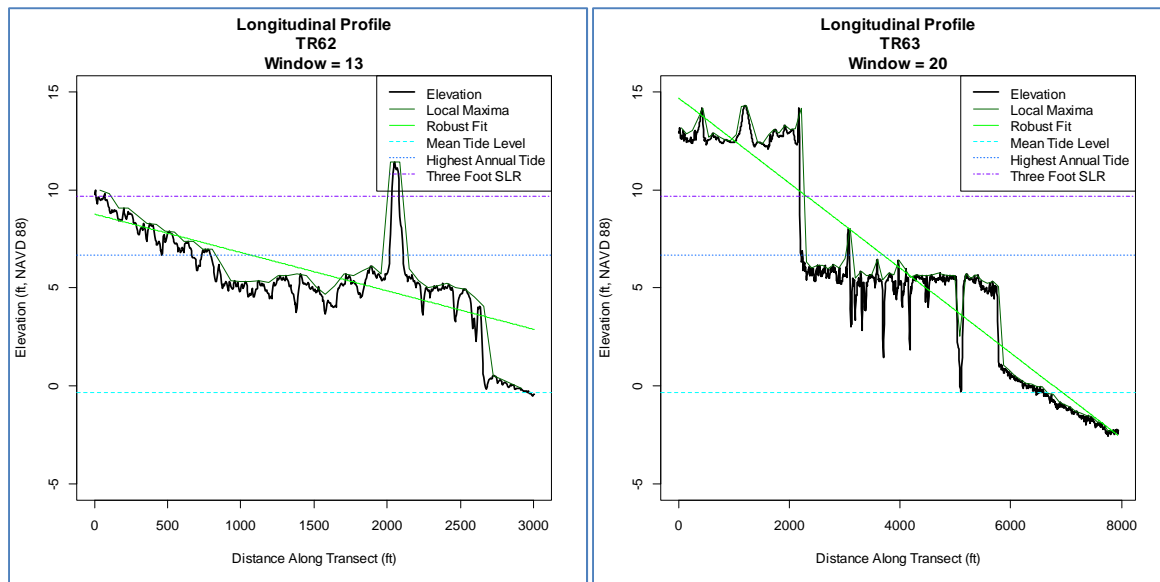


Figure 15. Two example longitudinal profiles, for the three tidal restrictions shown in Figure 14. Horizontal reference lines are for MTL (bottom of tidal wetland elevations), HAT (maximum elevation for development of tidal wetland) and HAT plus three feet, to provide an estimate of possible future extent of tidal wetlands.

It is worth looking at the example longitudinal profiles in Figure 15 in detail. In the left hand panel, the candidate tidal restriction is a road that crosses the valley at a location with intertidal wetland areas both upstream and down. Thus this site offers a good example of a potential high value restoration site.

On the right hand panel, the downstream candidate restriction is a road that crosses the valley at intertidal elevations (it’s the moderately tall spike at a distance of about 3,000 ft. along the transect). Intertidal elevations occur both upstream and downstream of this road as well, making it another attractive restoration target. The longitudinal profile also shows an additional tidal restriction upstream (TR64). This restriction is a

²⁷ Using the “Stack Profile” tool in the 3d Analyst extension.

²⁸ Spacing is determined by the software, which “densifies” each line before extracting elevations; no details are available on the algorithm used for deciding point spacing. It appears the software places one point within each pixel of the underlying elevation data, so spacing is not uniform.

²⁹ R Core Team 201, *Op. Cit.*

³⁰ Functions are available from CBEP upon request.

dam, with an impoundment upstream, showing elevations significantly higher than observed below the dam. The lower face of the dam occurs at salt marsh elevations, suggesting it may also be an attractive restoration opportunity. Unfortunately, our LIDAR data does not penetrate water, so we have no information on the bathymetry of the impoundment and consequently, we do not know what the bottom elevations are upstream of the dam.

We prepared these longitudinal profiles for each of the 128 candidate tidal restrictions (see Appendix A), and then used the profiles to determine: (1) whether the candidate tidal restriction has intertidal elevations both upstream and downstream; (2) whether the restriction impounds water; and (3) whether the site will become a tidal restriction under three feet of sea level rise. The goal was to determine which sites are worthy of additional investigation as a restoration opportunity. For dams and other impoundments, we considered the site a tidal restriction if the elevation of the downstream face of the dam or road that impounds the water is located at intertidal elevations.

Results of this analysis are shown in Table 13 and in Figure 16.

Thirty four (34) of the 128 candidate sites are not restrictions at all. Most are sites where roads run adjacent to tidal waters, but there is no terrain upstream of the road at intertidal elevations. An additional 18 sites cannot be confirmed as restrictions, usually because elevations upstream of the restriction lie close to the upper end of intertidal elevations. Many of these sites, however, will become restrictions under a three foot sea level rise scenario.

Using LIDAR data and GIS analysis we were able to confirm that 76 (60%) of our candidate tidal restriction are at appropriate elevations to affect tidal wetlands. These sites will now become the focus of more detailed analysis to determine whether they offer good opportunities for restoration. From the longitudinal profile data alone, we cannot determine whether the structures that cross the tidal areas are significant tidal barriers or not, although our experience with similar sites suggest that most probably are.

Table 13: Results of analysis of longitudinal profiles for 128 candidate tidal restrictions around Casco Bay.

Cause of Restriction	Not a Restriction			Possible Restriction		Restriction	Total
	Not a Future Restriction	Possible Future Restriction	Future Restriction	Possible Future Restriction	Future Restriction	Future Restriction	
Rail	1					1	2
Road	7	1	14	2	2	44	70
Road with Impoundment	1			1	2	7	11
Dam	1	1		1	3	16	22
Other	1		1	4	3	8	17
None	6						6
Total	17	2	15	8	10	76	128

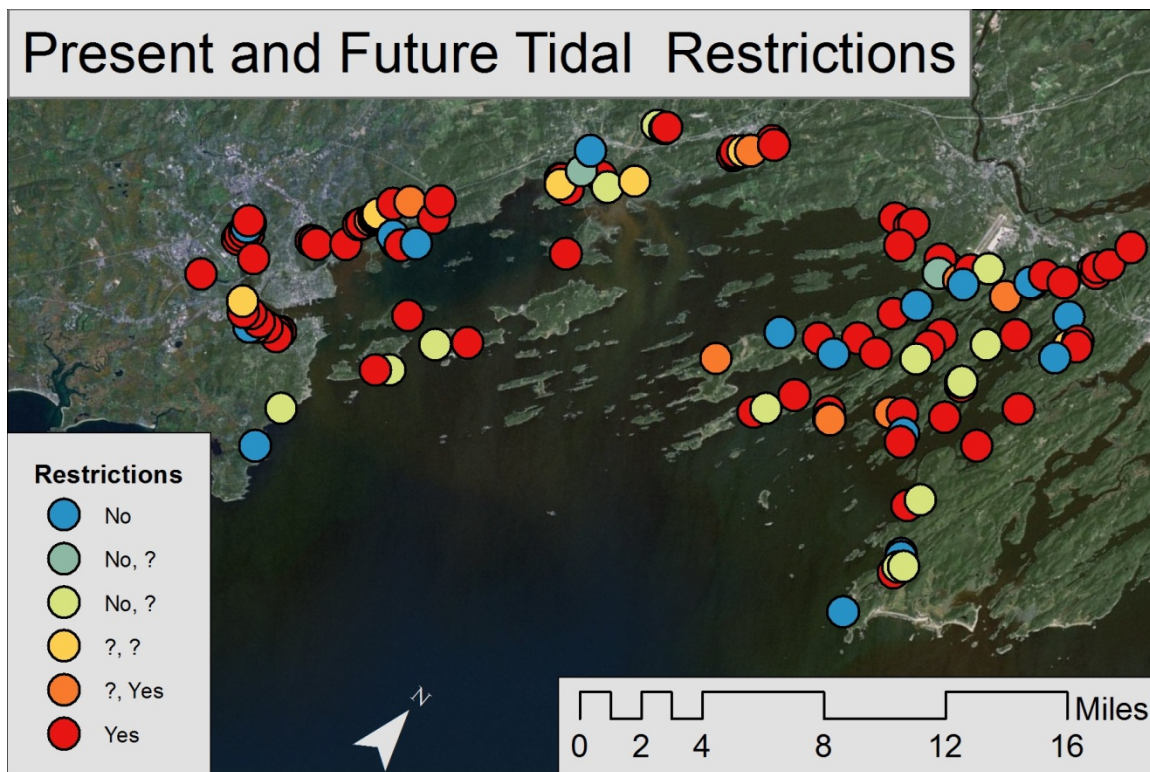


Figure 16. Graphical depiction of the results of the analysis of longitudinal profiles. The first word in the legend reflects whether each site is a restriction today, the second, whether it would be a restriction under three feet of sea level rise.

Analysis of Upstream and Downstream Elevation Transects

As part of the 2012 field assessment of tidal restriction sites, we regularly measured the height of the marsh surface along transects upstream and downstream of the tidal restriction. The reasons for collecting this data are several.

First, before opening up a significant tidal restriction, it is good practice to ensure that the exercise will not alter the character of the upstream wetland in unanticipated ways. Data on relative elevations and downstream can shed light on whether increased tidal flux may have unanticipated or undesirable effects upstream.

Second, tidal restrictions are likely to alter sediment dynamics. Restrictions could alter transport of allochthonous inorganic materials either by trapping terrestrially-derived sediments upstream, or by reducing landward transport of marine-derived sediments. Restrictions may alter processing of recent organic matter, by altering productivity and decomposition rates. Older organic deposits may be affected if restrictions alter sediment REDOX potential, sulfate availability or availability of other terminal electron acceptors. Some studies in Maine have suggested that elevations upstream of tidal restrictions may systematically differ from

those downstream.³¹ Collecting data on relative elevations upstream and downstream of tidal restrictions may offer a way to probe the frequency and significance of such processes.

An additional goal of this part of the study was to compare the speed, accuracy, and value of field-collected data with data derived from LIDAR coverages.

Field Data

Field data on relative upstream and downstream elevations was collected from 20 tidal restrictions around Casco Bay during the summer of 2012. Elevation data was collected with an optical auto level and stadia rod, referenced to a semi-permanent local benchmark. In most cases, the elevation of the local benchmark is not known, so the data can not be related back to NAVD without tying the benchmark to a known elevation.

The field data collection plan specifies that data should be collected along four cross sections at each site, two upstream and two downstream of each tidal barrier. Cross sections ran from the upland edge, as judged in the field, to the tidal channel. Where possible, a matching cross section would start on the opposite side of the tidal channel, and run to the uplands on the other side of the wetland. Data collected along each cross section consisted of a minimum of ten and a maximum of twelve elevations. Ten measurements were collected at evenly spaced points. Where necessary, an additional elevation was taken at one or both ends of the cross section to characterize the channel or upland transitions. Spacing of measurements varied, depending on the length of the cross section.

In practice it proved impossible to locate four suitable cross sections at all locations, so complete data consisting of four transects was not collected at all locations.

We used a Trimble handheld WAAS enabled GPS receiver to record the approximate position of the endpoints of all cross sections, to facilitate later comparison with LIDAR-derived elevations.

LIDAR-derived Elevations

We created draft elevation cross sections in GIS by drawing straight lines between the GPS positions of the endpoints of each cross section. Because of low precision of the GPS-derived positions (especially in narrow valleys) and several recording errors in the field data, several cross sections created this way were poorly located for characterizing the wetlands. We edited the draft GIS cross sections by hand, with reference to LIDAR and aerial photography to ensure that they ran from tidal channel to upland edge as had the field cross sections. Because of this editing process, field-derived and GIS derived cross sections do not correspond exactly.

We derived the elevations of points along those cross sections in GIS using the “Stack Profile” tool from the ArcGIS 3D Analyst extension. We crafted graphics functions in the statistical package “R” to draw upstream and downstream comparisons.³² We also calculated median elevations along each cross section. We used a scaled version of the Median Absolute Deviation (MAD) as a robust estimate of scale.³³ Figure 17 shows an

³¹ Linell, S. 1994. A Survey of impounded salt marshes in southern Maine. Masters thesis, Antioch New England graduate School. Antioch University.

³² Available upon request.

³³ The scaled MAD converges to the conventional standard error for large sample sizes derived from normal distributions.

example of the graphical comparison of the upstream and downstream transects, in this case site TR08, located in South Portland.

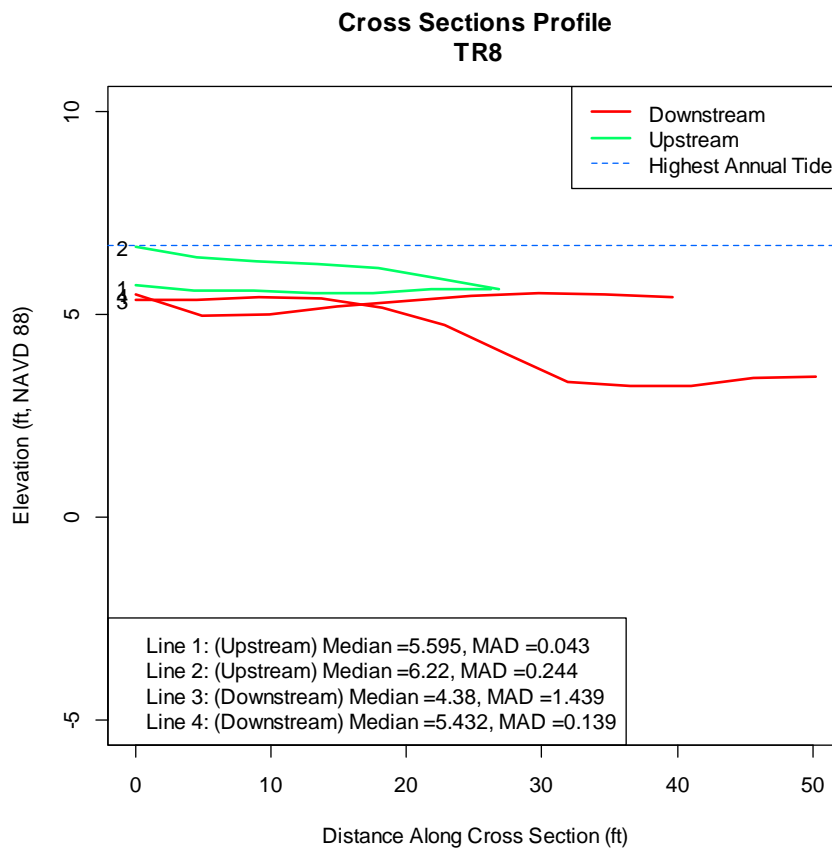


Figure 17. Plotting elevation versus distance on four cross sections of the tidal marsh at tidal restriction TR08, in South Portland. Here, upstream elevations on both upstream cross sections are higher than (almost all) elevations along the downstream cross sections.

Data Comparison

After removing sites with incomplete data, sites not at one of our tidal restrictions, and data for which there were obvious data quality problems, we were left with complete data from both field and LIDAR derived data for only on eleven tidal restrictions

Upstream-downstream differences in median elevation derived from the two data sources are highly correlated ($r = 0.774$), suggesting that the LIDAR and field-derived data are providing closely related, but not identical, information. The correlation coefficient is dominated by a few sites with large positive (i.e., upstream elevations are higher) differences between upstream and downstream elevations. For small displacements of under about $\frac{1}{2}$ of a foot, the relationship is weak. That is not surprising, as differences of that scale are within the margin of error for the underlying LIDAR data and are similar to variation in elevations observed in the field across a marsh transect.

Conclusions

The high correlation between LIDAR- derived and field-derived comparisons suggests that, for these purposes, the two approaches are more or less interchangeable. However, there are several advantages to using the LIDAR-derived data, at least as a screening tool.

- (1) it is far less labor intensive to collect
- (2) The data is automatically referenced to NADV88, and
- (3) It is less prone to data collection, recording, and management errors.

Table 14. Differences between the median upstream and median downstream elevations derived from LIDAR and field data. No quantitative error estimates are offered here, because it is not obvious how to assess uncertainty in this strongly spatially structured data. Differences are often similar in magnitude to variation across individual transects.

Site	LIDAR- Derived Estimates Difference in Medians	Field-Derived Estimates Difference in Medians
TR8	0.484	-0.210
TR18	0.393	0.400
TR44	-0.360	-0.280
TR56	1.124	1.525
TR60	0.495	0.450
TR62	-0.025	0.415
TR63	0.030	-0.610
TR67	3.263	1.520
TR88	0.590	0.605
TR89	-0.095	-0.105
TR96	-0.083	0.230

Several locations exhibited elevations upstream of a tidal restriction that were lower than elevations downstream. With a sample size of only eleven sites, we do not yet have enough information to examine how those sites may differ from the others. We also do not yet have enough experience with this style of analysis to determine how reliable the results may be.

Future work will focus on (1) increasing our sample size beyond the sites for which we also have field-derived data, (2) standardizing transect placement to increase comparable data for different sites, (3) comparing results of transect-derived upstream-downstream comparisons with comparisons derived by looking at elevations over selected areas and (4) testing hypotheses about what characterizes sites with lower upstream elevations.

Restoration and Sea Level Rise

A growing concern among restoration practitioners is that the long term value of tidal restoration projects may be compromised by the effects of sea level rise. In microtidal and mesotidal regions, restoration of intertidal habitats today may have a relatively short lifespan, as rising seas convert intertidal areas to subtidal habitat, thus altering the mix of ecosystem services provided by nominally restored coastal areas. The issue may be less pressing in Maine's macrotidal estuaries, but the question is still cogent.

It may also be of interest for restoration practitioners to evaluate the relative costs and value of investing in tidal restoration versus investing in protection of upland areas where tidal wetlands may migrate in future. Both these questions can be approached using LIDAR and tools described in this report.

Modeled Response of Restoration Sites to Sea Level Rise

To demonstrate these methods, we applied the tools developed in Part 2 of this report to potential tidal restoration sites around Casco Bay. We initially limited our analysis to the eleven sites for which we have complete field evaluations from 2012 as well as LIDAR data. We eventually supplemented those data with data candidate restrictions upstream of those locations because we realized that value of downstream restoration may be reduced if upstream restrictions are not themselves opened up to increase tidal flow.

For each tidal restoration site studied, we extracted hypsographic information for the area upstream of the tidal restriction. We then modeled effects of sea level rise on these areas, using the methods outlined in Part 2 of this report. Models were run assuming three feet of sea level rise in 100 years and an accretion rate of 2 mm per year. The 2mm per year accretion rate is similar to average historic rates in Maine.

For each site, we extracted information from the models on projected future wetland area based on elevation. In particular, we estimate the total land area upstream of each tidal restriction at wetland elevations at 0, 25, 50, and 100 years. We also record the minimum and maximum total wetland area projected over the 100 year period, and calculated the net change in wetland area over time.

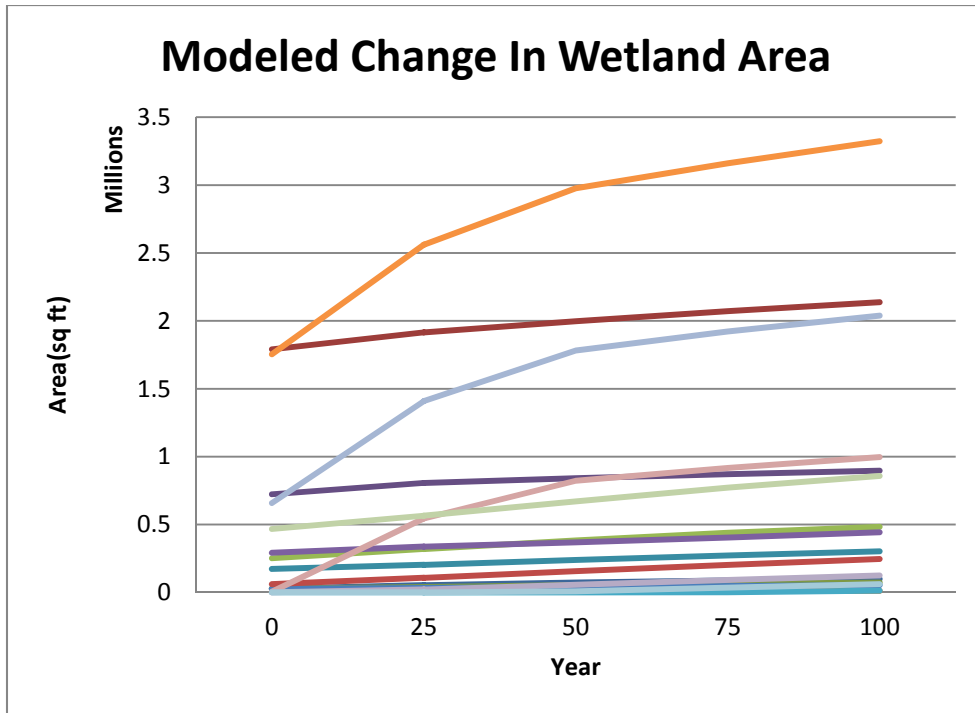


Figure 18. Predicted change in wetland area upstream of 17 tidal restrictions around Casco Bay. This sample included two sites that are above intertidal elevations today. All sites are projected to gain wetland area with sea level rise.

Table 15. Projected net change in low marsh, high marsh, and total wetland area upstream of 17 tidal restrictions around Casco Bay. N/A represents sites where percent change cannot be calculated because no relevant wetland is present today. All potential restoration sites studies are projected to gain low marsh, and all sites gain total wetland area, but some lose high marsh as a consequence of sea level rise.

Site	Percent Change In Area		
	Low Marsh	High Marsh	Entire Wetland
TR08	N/A	199%	271%
TR18	423%	-67%	19%
TR20 ¹	N/A	76%	164%
TR21 ¹	1027%	-68%	24%
TR44	4188%	-18%	75%
TR46	N/A	124%	215%
TR56	957%	23%	106%
TR60	348%	295%	305%
TR62	1504%	4%	92%
TR63 ²	98836%	-41%	52%
TR67	N/A	N/A	N/A
TR88	7.767555135	8%	89%
TR89 ³	624.2857143	127%	210%
TR90 ³	N/A	20327%	20338%
TR96	1375.615385	-12%	84%
TR97 ⁴	N/A	21657%	21683%
TR98 ⁴	N/A	N/A	N/A

1: Sites are upstream of TR18
2: A dam upstream at intertidal elevations (TR64) may offer additional opportunities for wetland expansion under sea level rise if it is removed.
3: Sites upstream of TR88. TR90 is above present-day intertidal elevations.
4: Sites upstream of TR96. TR97 sits very close to HAT, so it has little tidal marsh upstream. TR98 is entirely above tidal elevations today.

Discussion

It is clear that creative use of LIDAR data can provide significant insight into tidal marsh restoration. Here we have demonstrated several techniques for using LIDAR data to identify, evaluate, and prioritize tidal marsh restoration opportunities. While the techniques pioneered here are aimed at tidal restrictions, we believe they can readily be extended or adapted to use on other kinds of tidal restoration.

Longitudinal profiles provide a relatively simple screening tool for evaluating tidal wetland restoration opportunities in terms of present-day and future tidal datums. The approach involves direct application of a readily available tool in ArcGIS (the “Stack Profile” tool from 3d Analyst). While we exported the data produced by “Stack Profile” to “R” to facilitate data analysis, that would not be necessary for working with a

small number of sites. Elevations could be graphed directly in GIS, or exported to Excel. No complex processing or modeling is necessary.

Extraction of elevations on an area basis forms the basis the tools we have developed examine and analyze the full hypsometric curve for target areas. We have only begun to explore these methods in the context of evaluating restoration opportunities. For example, the methods allow us to calculate the net area of tidal wetland on a year by year basis in future under different sea level rise and sediment accretion scenarios.

In the Casco Bay Region, the value of restoration of most tidal restrictions is likely to increase, not decrease over time. Most tidal restrictions in this region occur where roads or other linear infrastructure cross tidal valleys. Thus most opportunities for restoration of tidal flux to existing wetlands occur in Head of Valley wetland complexes. In Part 2 of this report, we demonstrated that most Head of Valley wetland complexes are expected to increase in tidal wetland area in response to sea level rise. It should come as little surprise, then, that the tidal restrictions we examined also increase in wetland area as sea levels rise.

Part 4: Development of Outreach Materials

Introduction

One overall goal of the project was to develop methods to make the results of these investigations accessible to local officials, town planners, land trusts and local citizens. While the technical analyses going on in Parts 2 and 3 of this report were underway, a parallel effort was underway to craft materials to communicate major findings to local communities.

Here along Casco Bay, with our relatively steep shorelines, the most important information to convey to local communities revolves around the landward migration of wetland, the future location of the intertidal zone, identification of areas where marsh migration is likely to conflict with existing infrastructure. More subtle distinctions, such as specifics of whether wetland will increase or decrease overall, or how wetland change will depend on sedimentation rates are of secondary importance. The communications package we developed reflects those priorities.

Fourteen municipalities touch the shoreline of Casco Bay.³⁴ We prepared draft communications packages for each municipality. We prepared a series of maps for each town at a 1:9,000 scale. The maps focus on areas where significant wetland change or landward migration of the intertidal zone are anticipated under significant (3 ft.) sea level rise. The maps show both areas of significant wetland change (based on the wetland change data described in Part 1 of this report), and also areas where present or future areas of wetland may conflict with existing infrastructure.

The communications package for each town consists of:

- (1) A general introduction to the project.
- (2) A brief discussion of sea level rise in the Casco Bay Region.
- (3) An overview map for each town identifying area depicted in detail maps.
- (4) Detail maps showing for each of those areas.

An example communications package is attached to this report as Appendix B.

Development of “Conflict” Data

We wanted to highlight areas where expansion of wetlands may lead to conflict with existing development. There are two perspectives from which such information may be useful. First, this information could be used to supporting planning for whether and how to protect existing infrastructure from future tidal inundation. Second, this information could be used to assess whether future efforts to protect infrastructure will block landward migration of wetlands, and thus affect local or regional gains or losses of wetlands in response to sea level rise.

We tested several methods for identifying areas of potential conflict between developed land and future location of wetlands:

³⁴The towns are: Bath, Brunswick, Chebeague Island, Cumberland, Falmouth, Freeport, Harpswell, Long Island, Phippsburg, Portland, South Portland, West Bath, Yarmouth, and Cape Elizabeth

- (1) The MELCD data set available from the Maine Office of GIS includes data on developed land use categories. We tested whether these land use categories provide a useful surrogate for areas where conflict with wetland migration is likely.
- (2) We examined whether a buffer around the MELCD developed land uses would better serve that function.
- (3) We looked at whether application of a buffer around areas of impervious surfaces³⁵ would provide a useful indicator of future conflict with development.

After reviewing the “conflict” data layers produced each way, we concluded that the MELCD cover classes are not well suited to this purpose. These data focus on broad land use categories, not structures. By including areas associated with dwellings and other development within their developed land categories, MELCD cover classes are likely to overestimate the area that will be strongly defended. By failing to identify the locations of individual structures, on the other hand, they also may overlook locations where conflict may be significant.

Our final “conflict” data layers are based on looking at areas of present-day impervious surfaces. We calculated a 75 foot buffer around areas of impervious surfaces based on a 1m resolution impervious cover data from 2007. Any area within the 75 foot buffer, which also overlapped (current or projected) tidal marsh elevation, was considered to have the potential for conflict between human activity and landward migration of intertidal areas. Conflict will not occur at all such locations, but almost all areas where problems will arise in the future will fall within these areas.

To develop the “conflict” data layers, we first converted the 2007 impervious cover data from raster to polygon format. We then calculated a 75 foot buffer around the impervious polygons. We overlaid the impervious cover buffer data on the wetland change data layers for one foot, two foot and three foot sea level rise scenarios.³⁶

Reviewing and Revising the Materials

We met with Anna Breinich, Brunswick’s Director of Planning and Development, to gather feedback on the information package we had assembled. As chance would have it, Brunswick has also been working with Peter Slovinsky, Steve Walker, and students at Bowdoin College on similar projects. Steve Walker also attended the meeting.

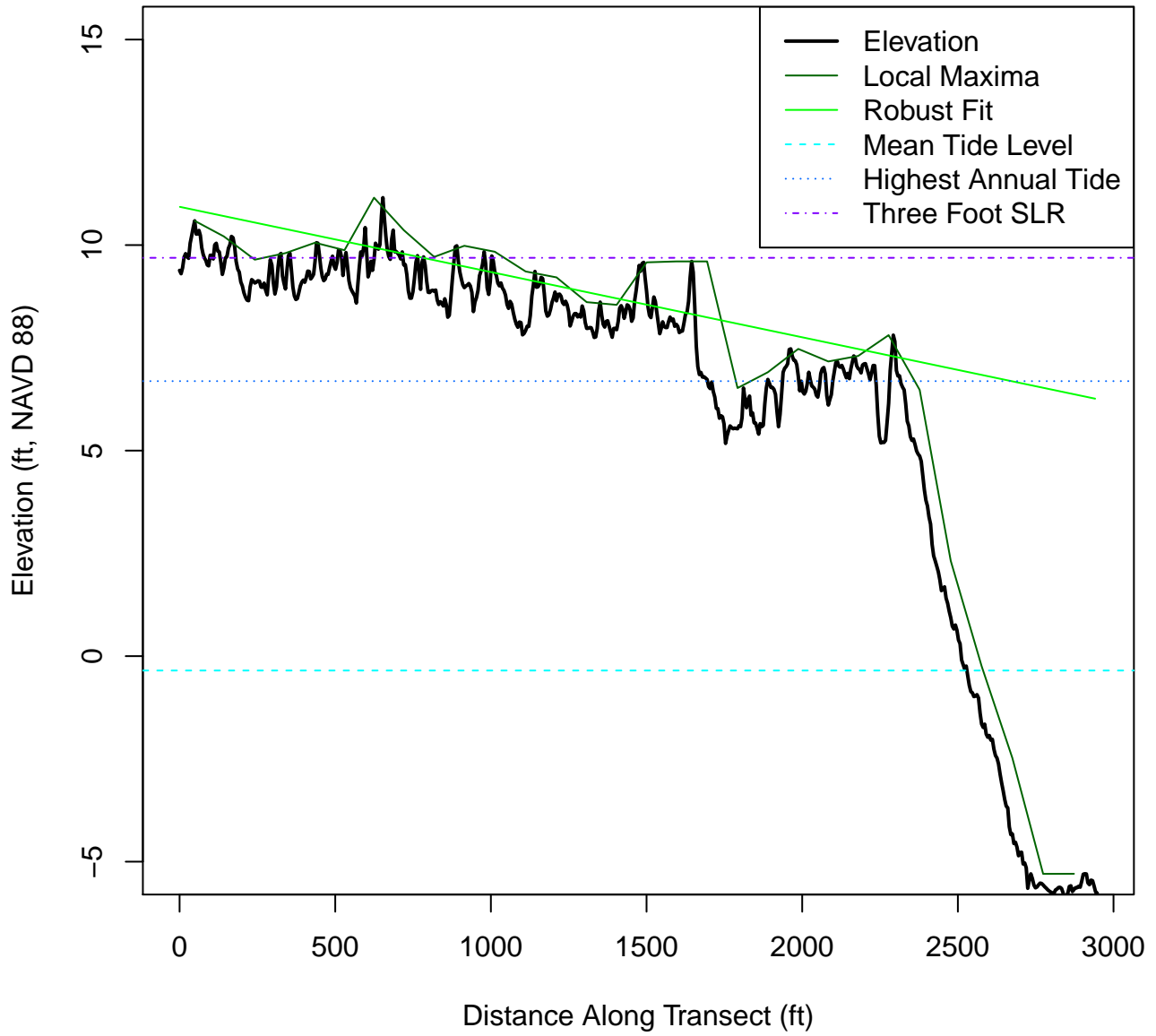
The participants in the meeting made several suggestions to improve on our draft maps. They suggested that we should overlay parcel boundaries over the wetland conflict maps, and we should include data on known tidal barriers. Both have been added to the example materials provided in Appendix B.

³⁵ We received 2007 data on impervious surfaces directly from the Maine Department of Inland Fisheries and Wildlife in June of 2012.

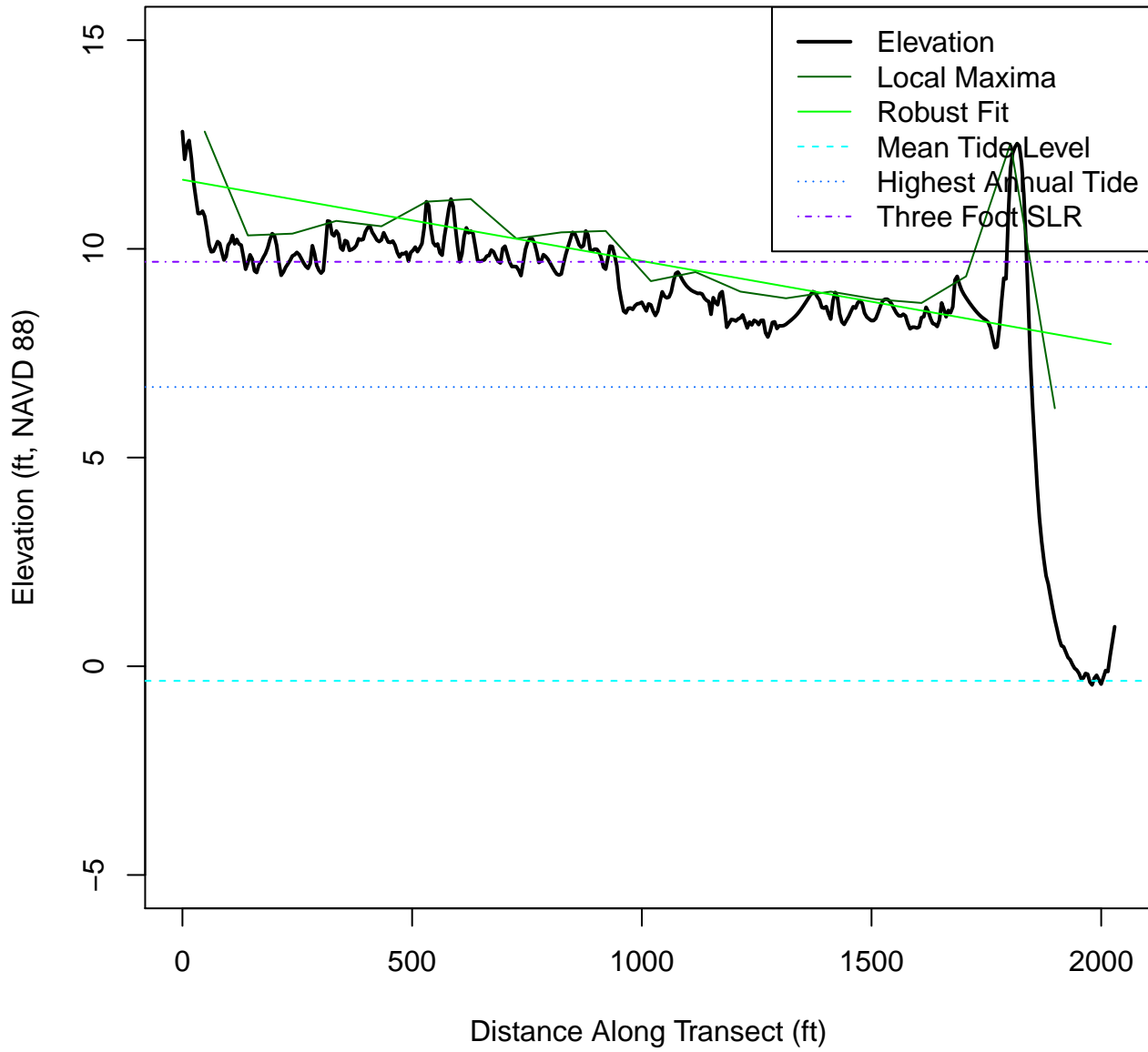
³⁶ The resulting data layers are included in the data distribution as “Conflicts_1ft_SLR”, “Conflicts_2ft_SLR”, and “Conflicts_3ft_SLR”

Appendix A: Longitudinal Profiles for 128 Candidate Tidal Restoration Sites.

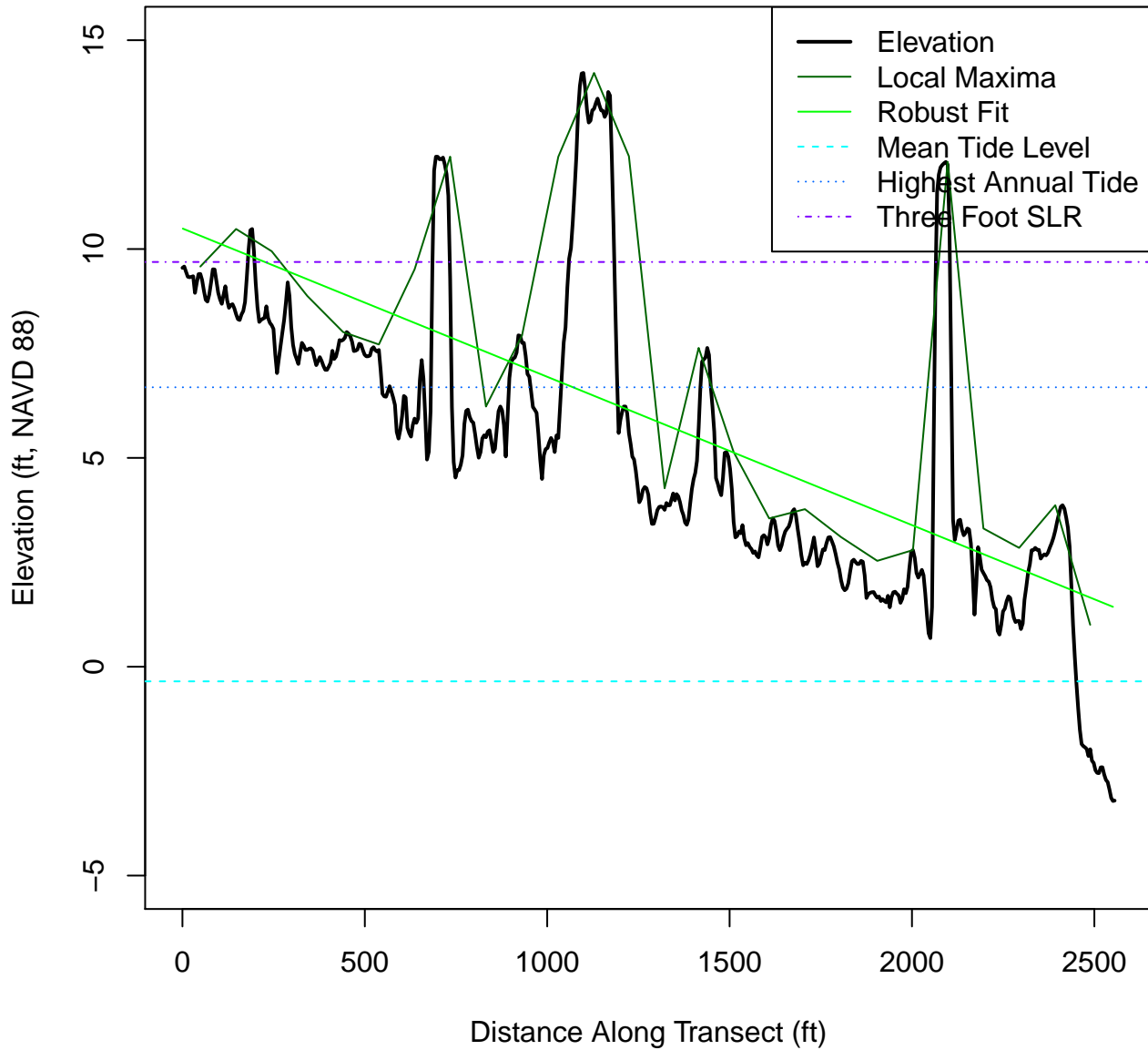
**Longitudinal Profile
TR01
Window = 20**



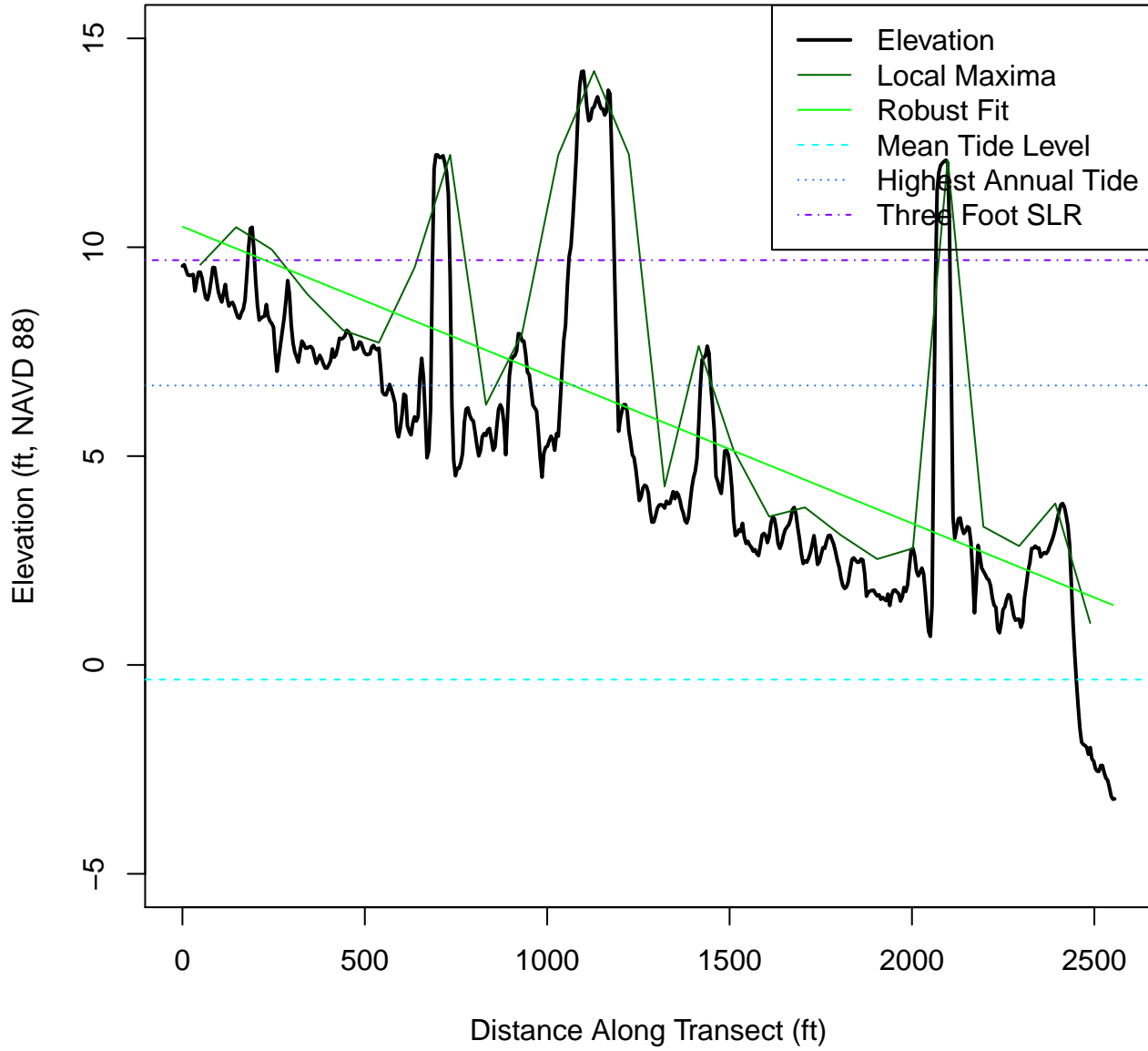
**Longitudinal Profile
TR02
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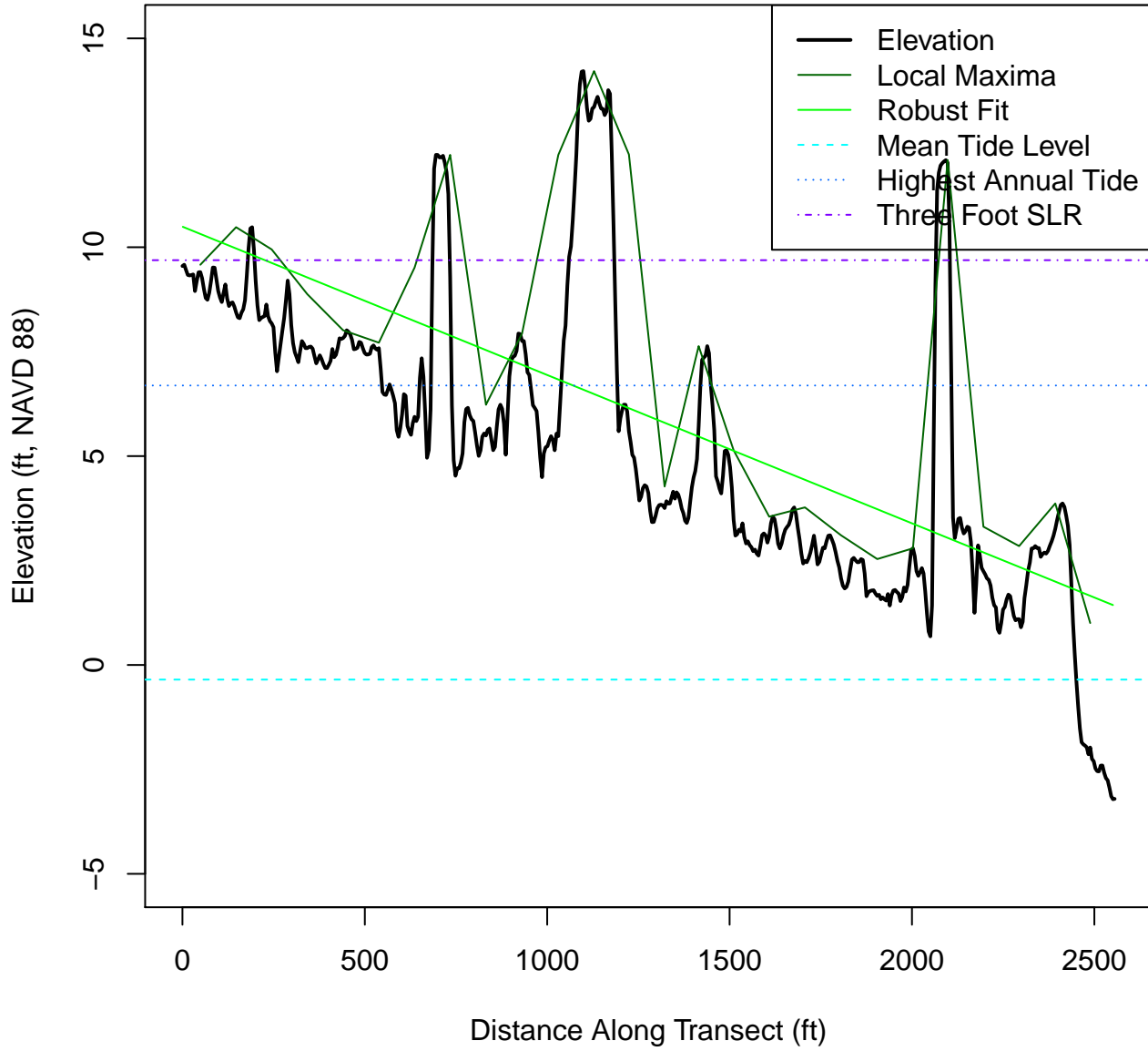
**Longitudinal Profile
TR03
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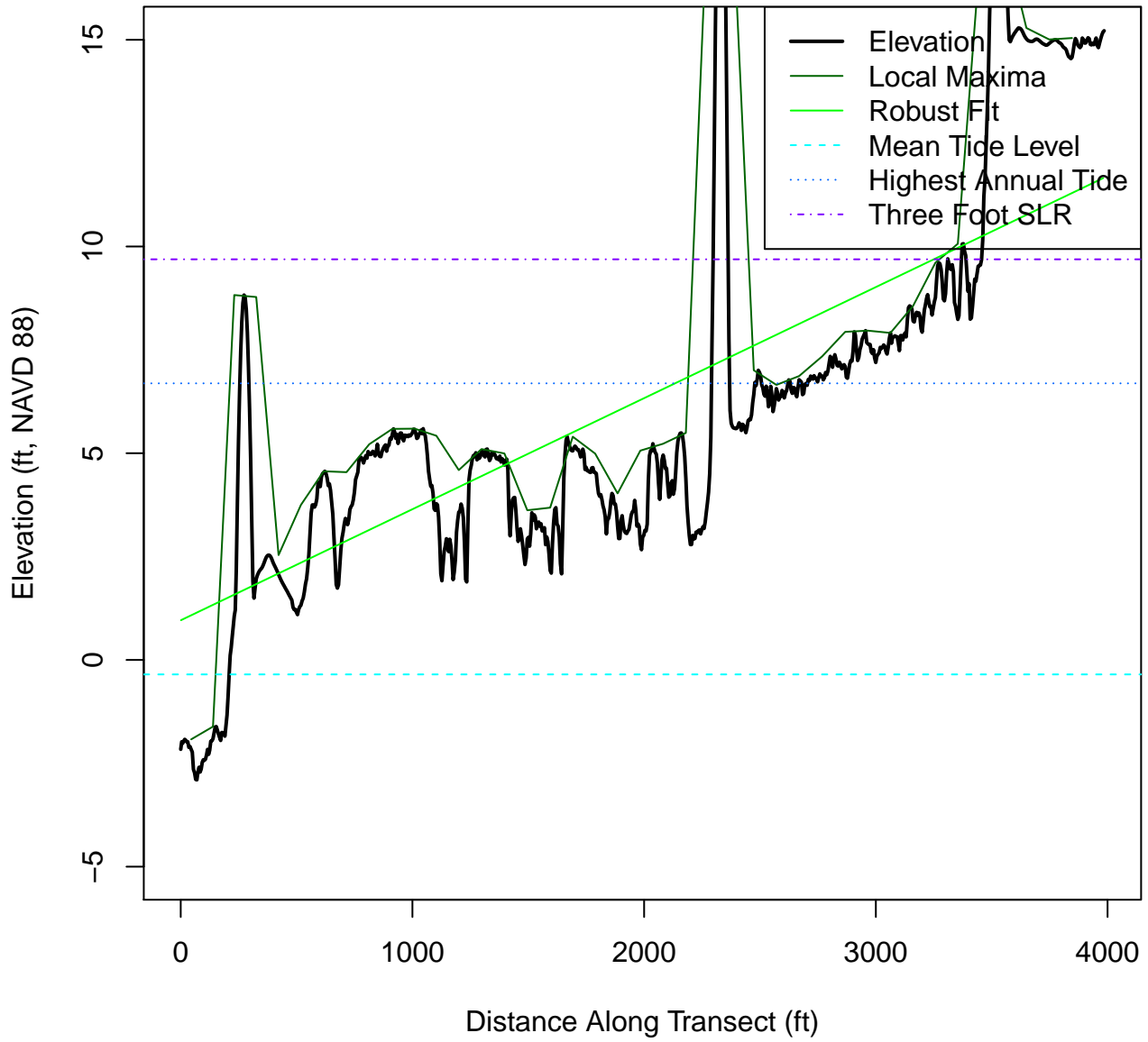
**Longitudinal Profile
TR04
Window = 20**



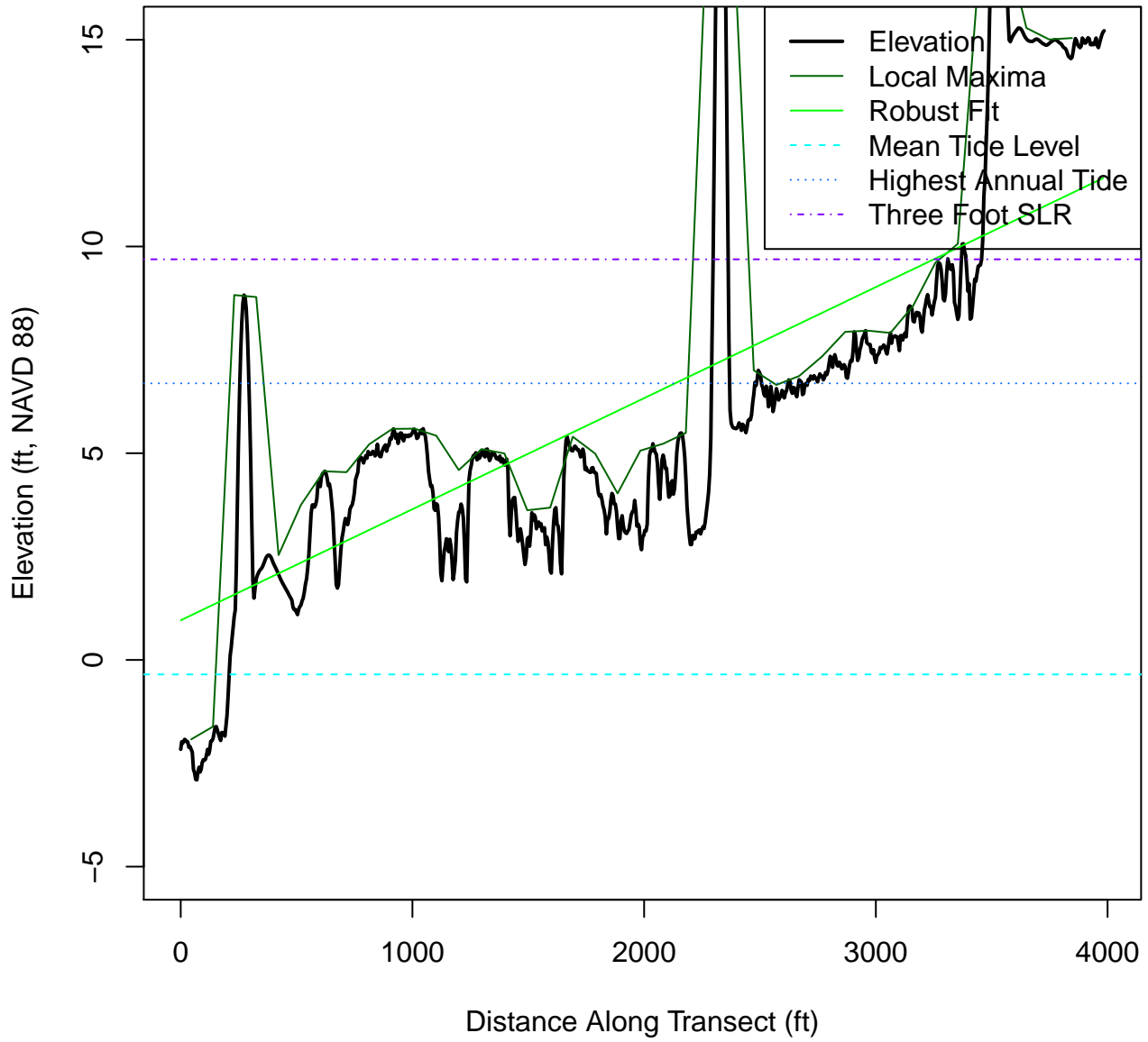
**Longitudinal Profile
TR06
Window = 20**



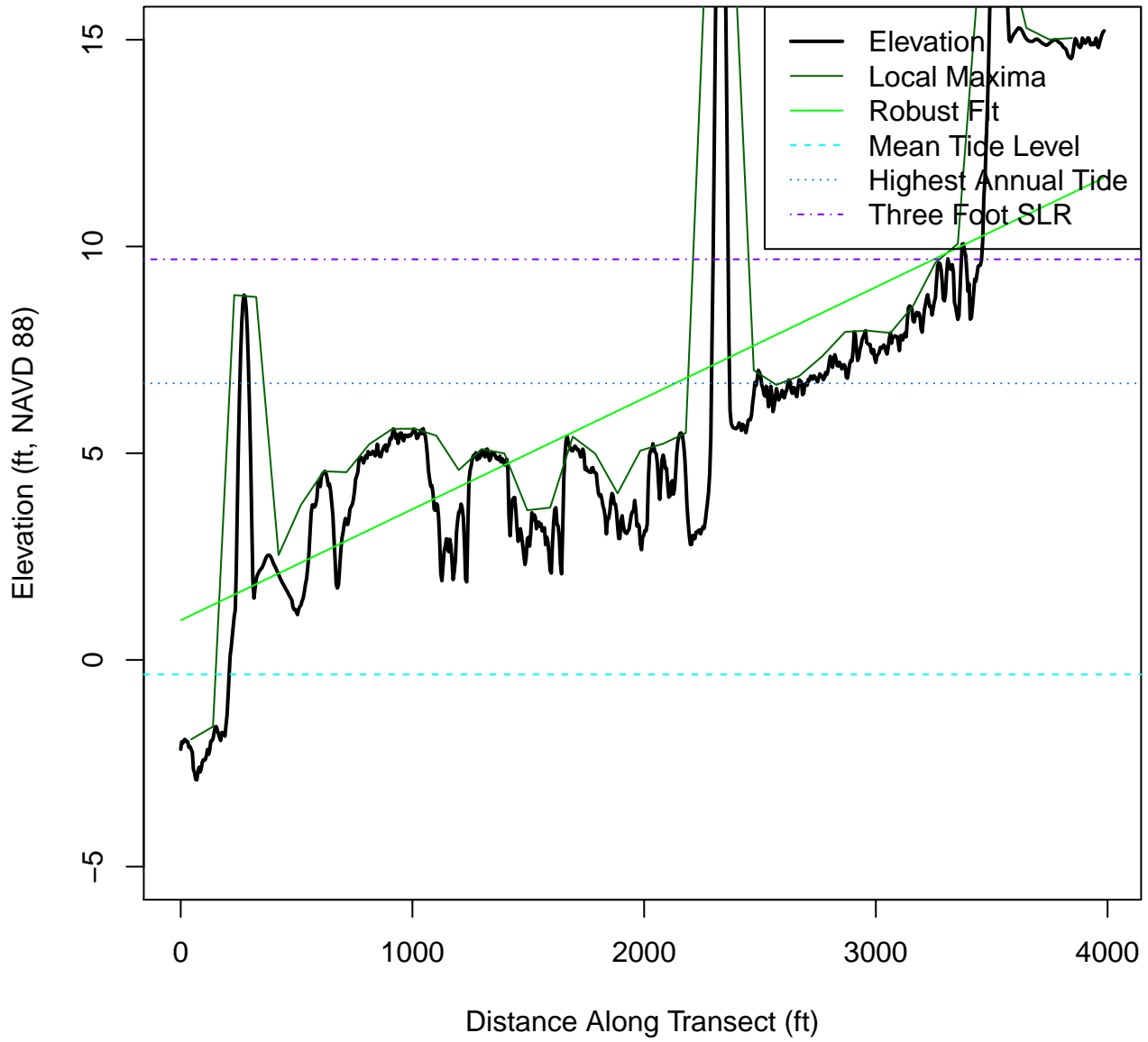
**Longitudinal Profile
TR07
Window = 20**



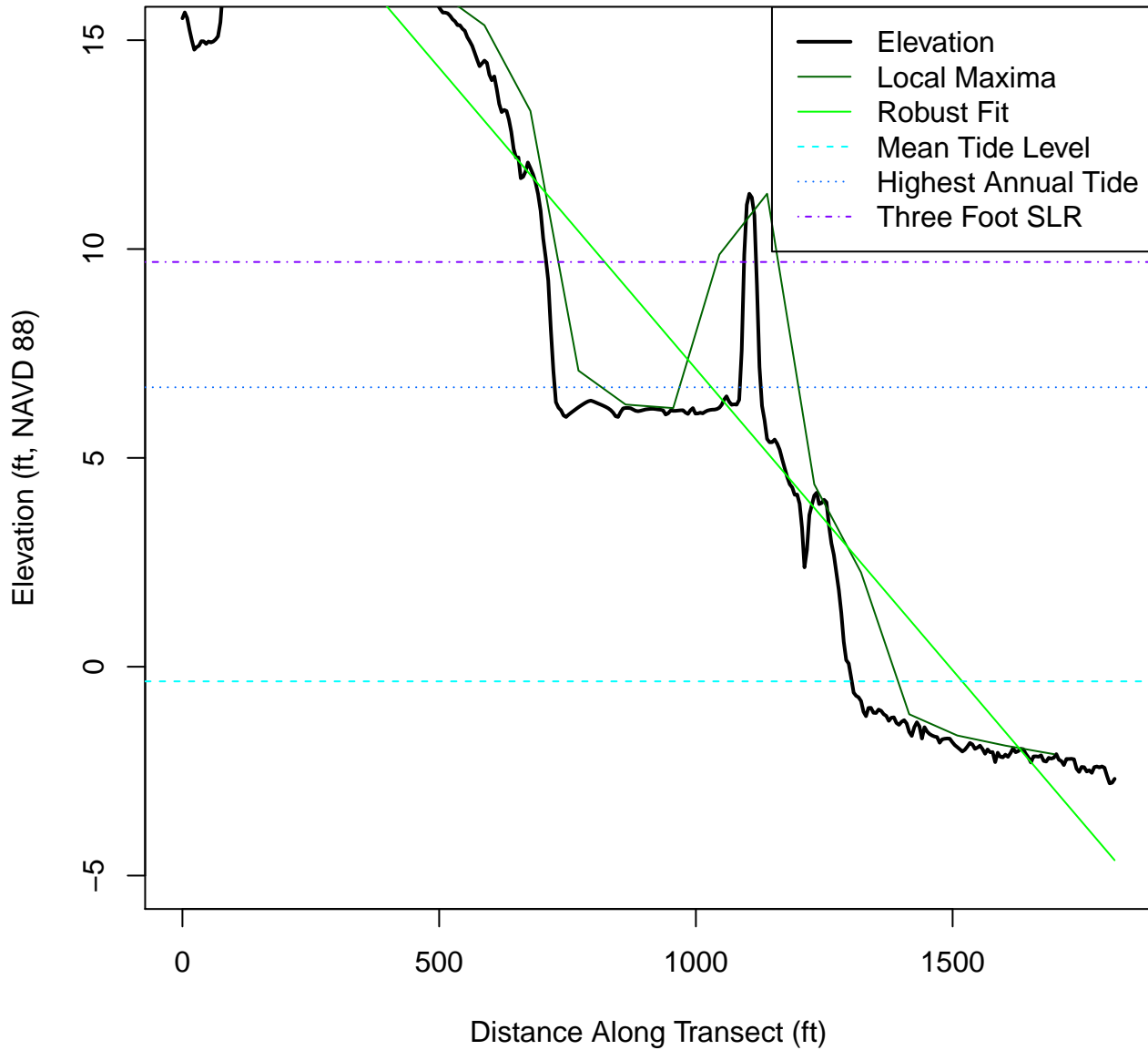
**Longitudinal Profile
TR08
Window = 20**



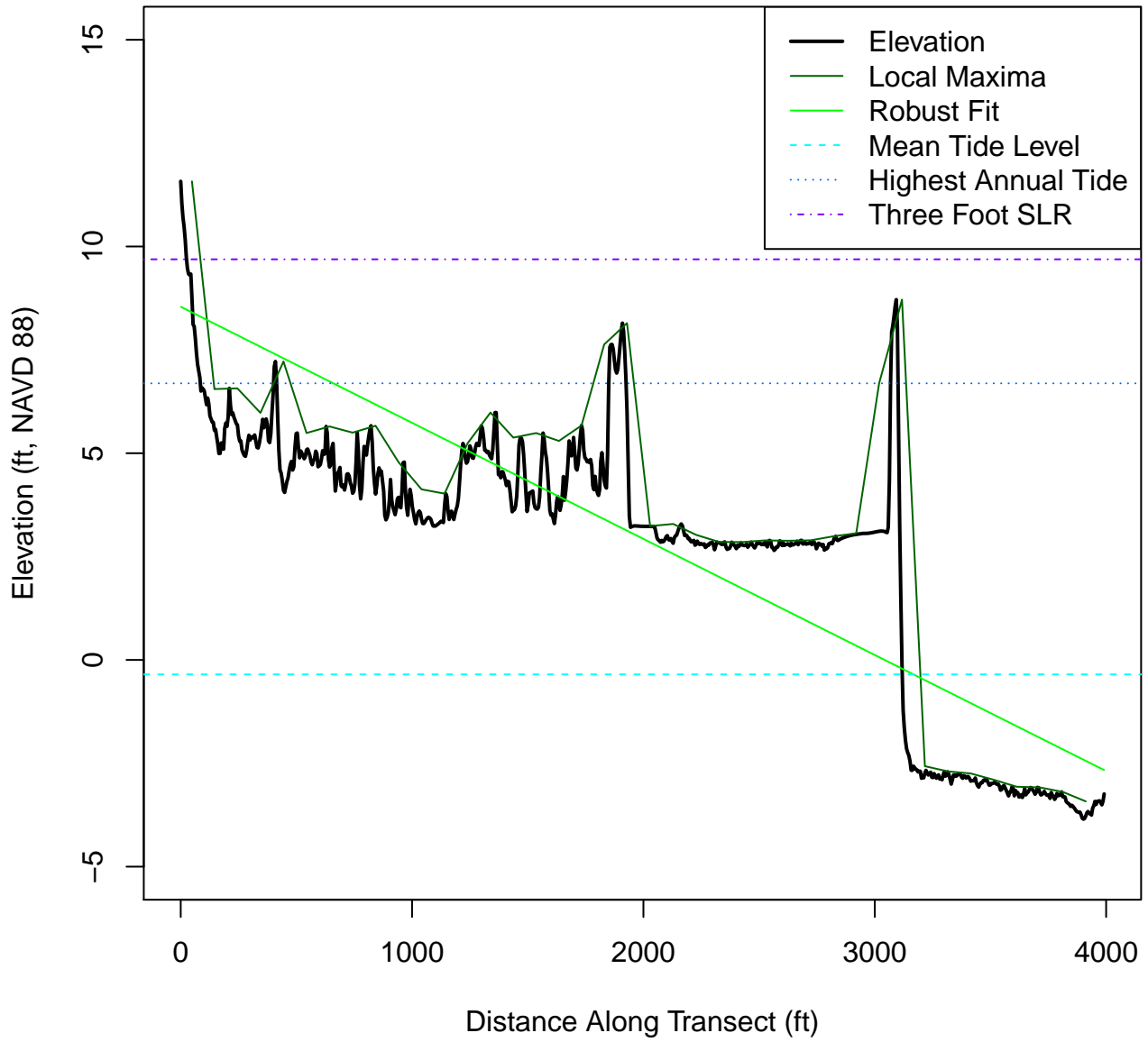
**Longitudinal Profile
TR09
Window = 20**



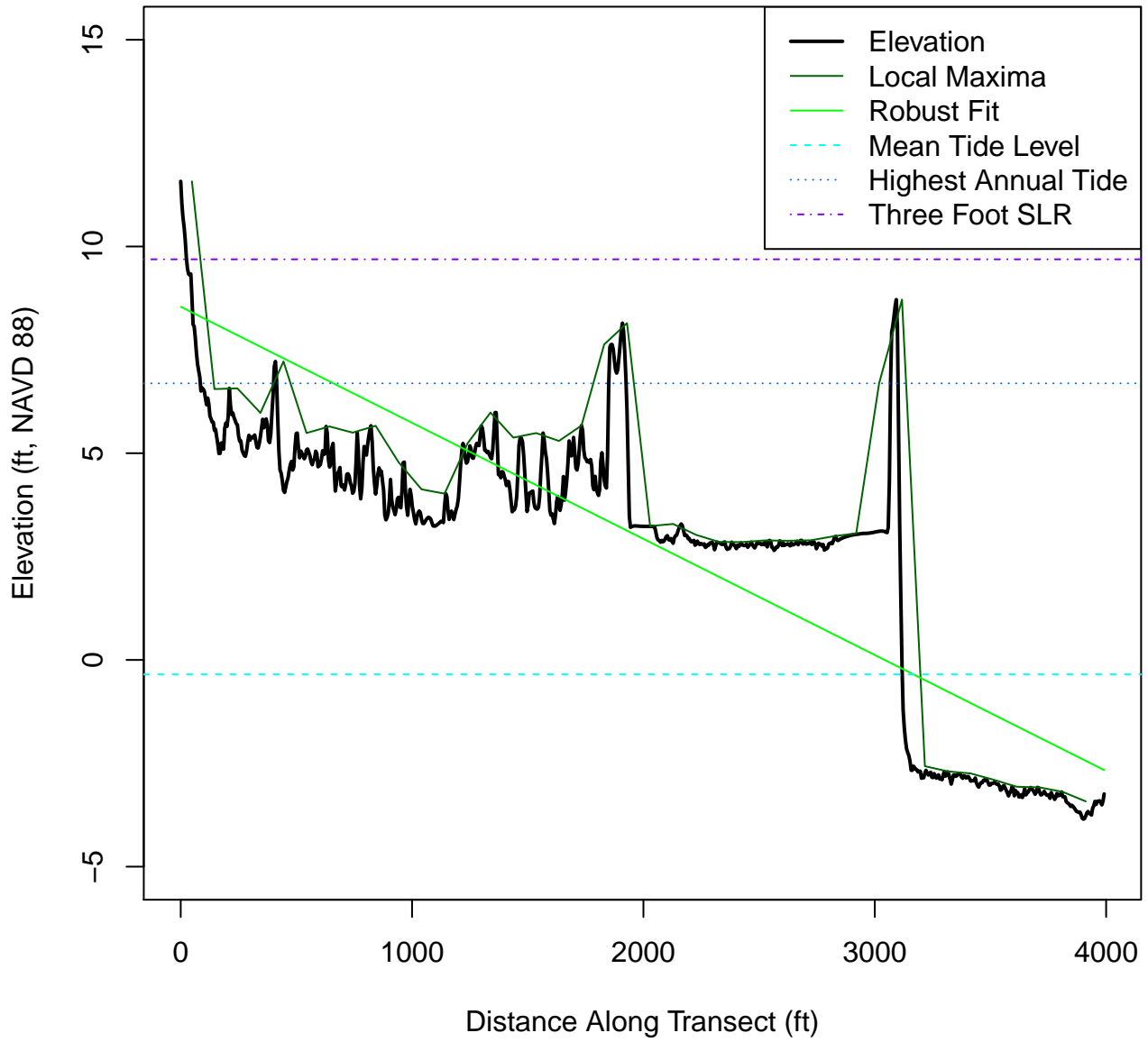
**Longitudinal Profile
TR10
Window = 19**



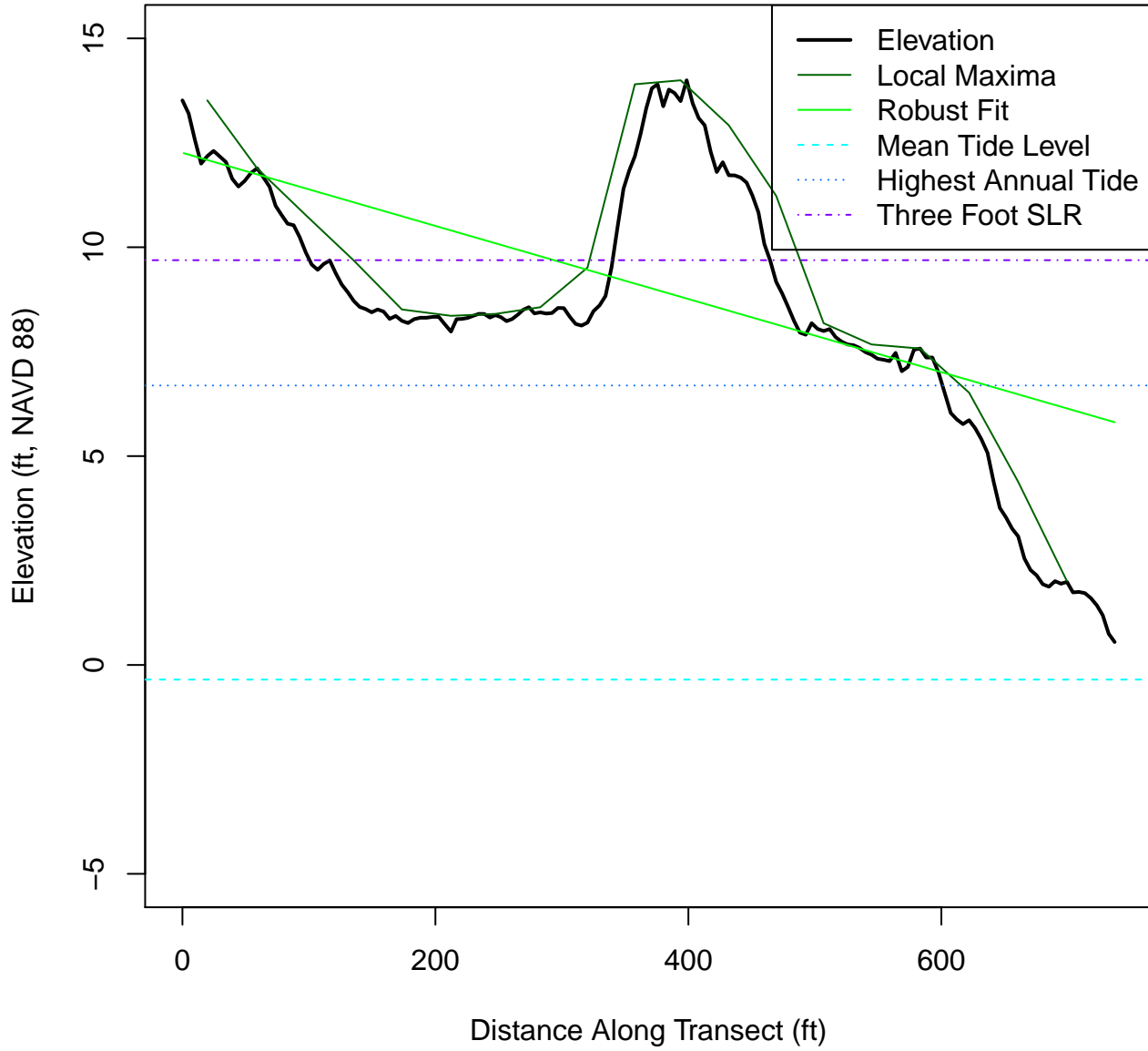
**Longitudinal Profile
TR11
Window = 20**



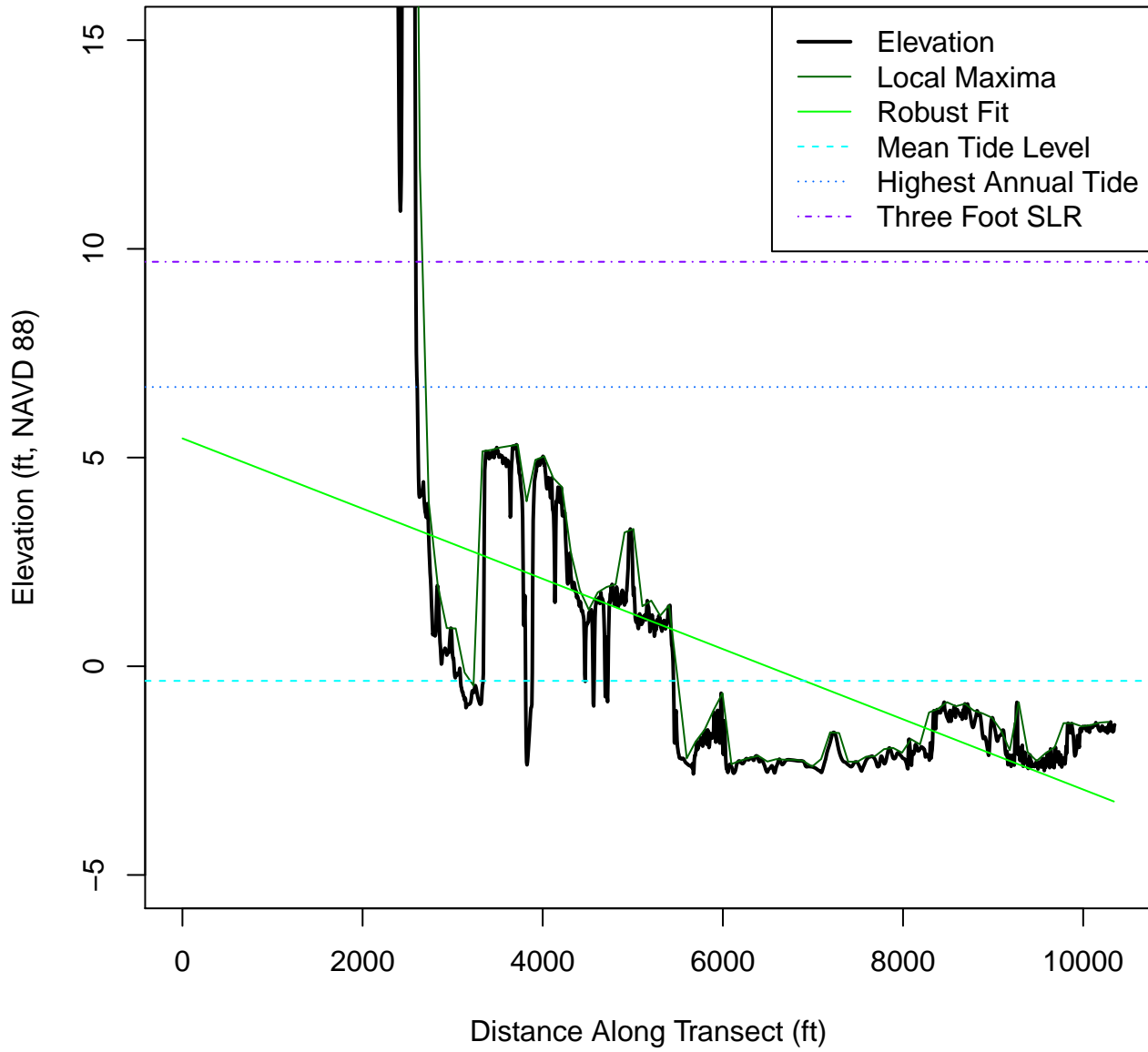
**Longitudinal Profile
TR12
Window = 20**



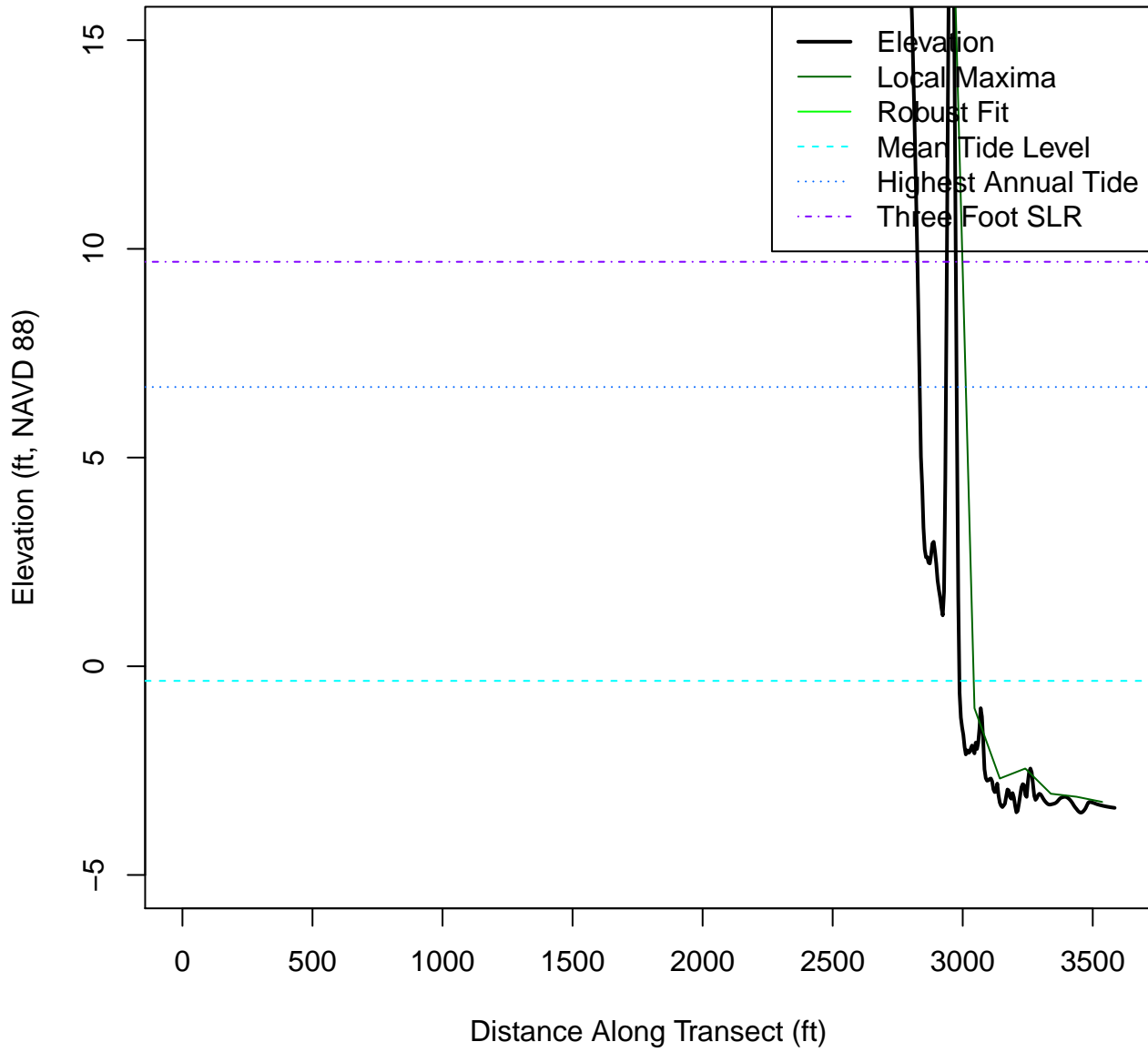
**Longitudinal Profile
TR13
Window = 8**



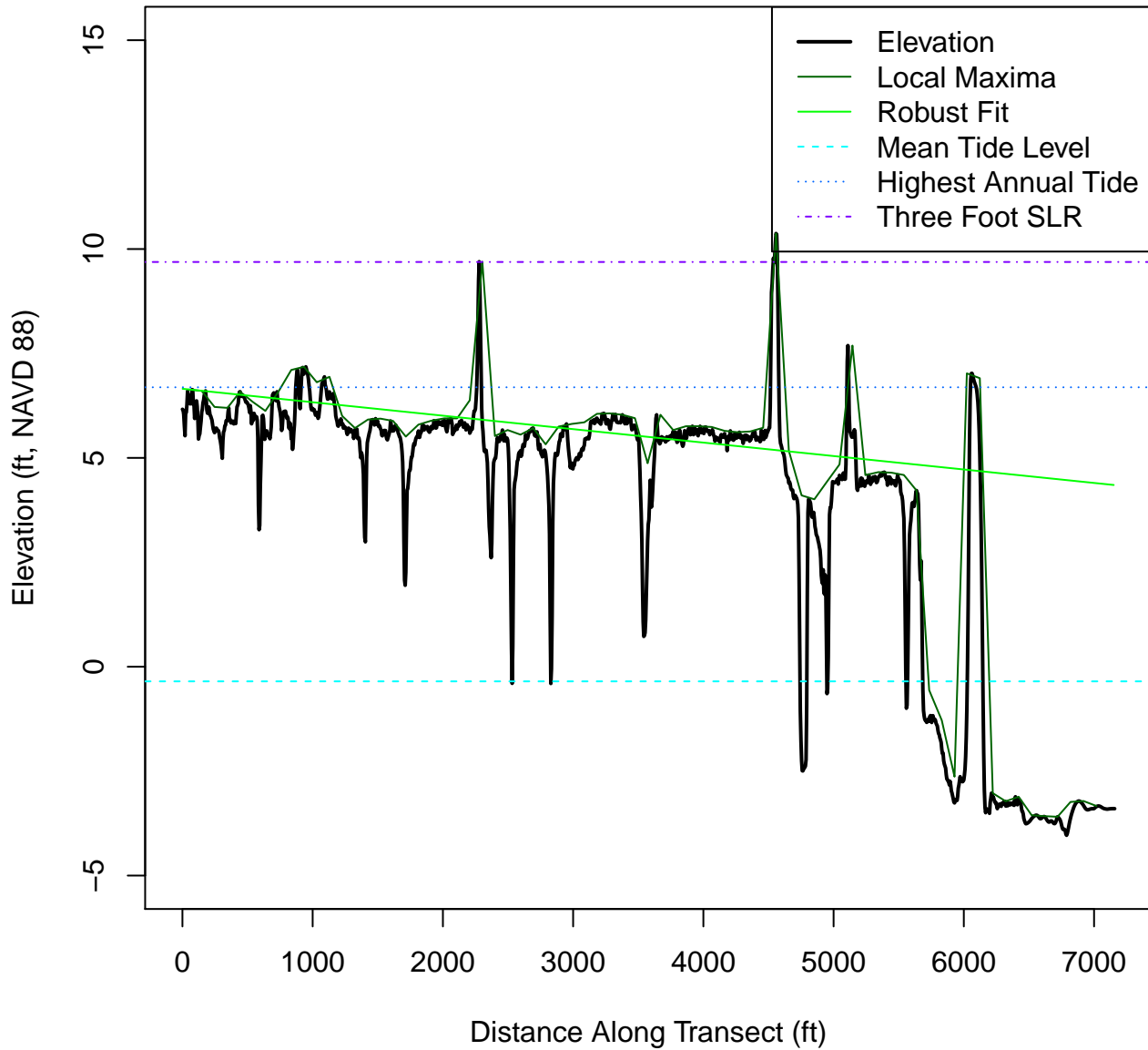
**Longitudinal Profile
TR14
Window = 20**



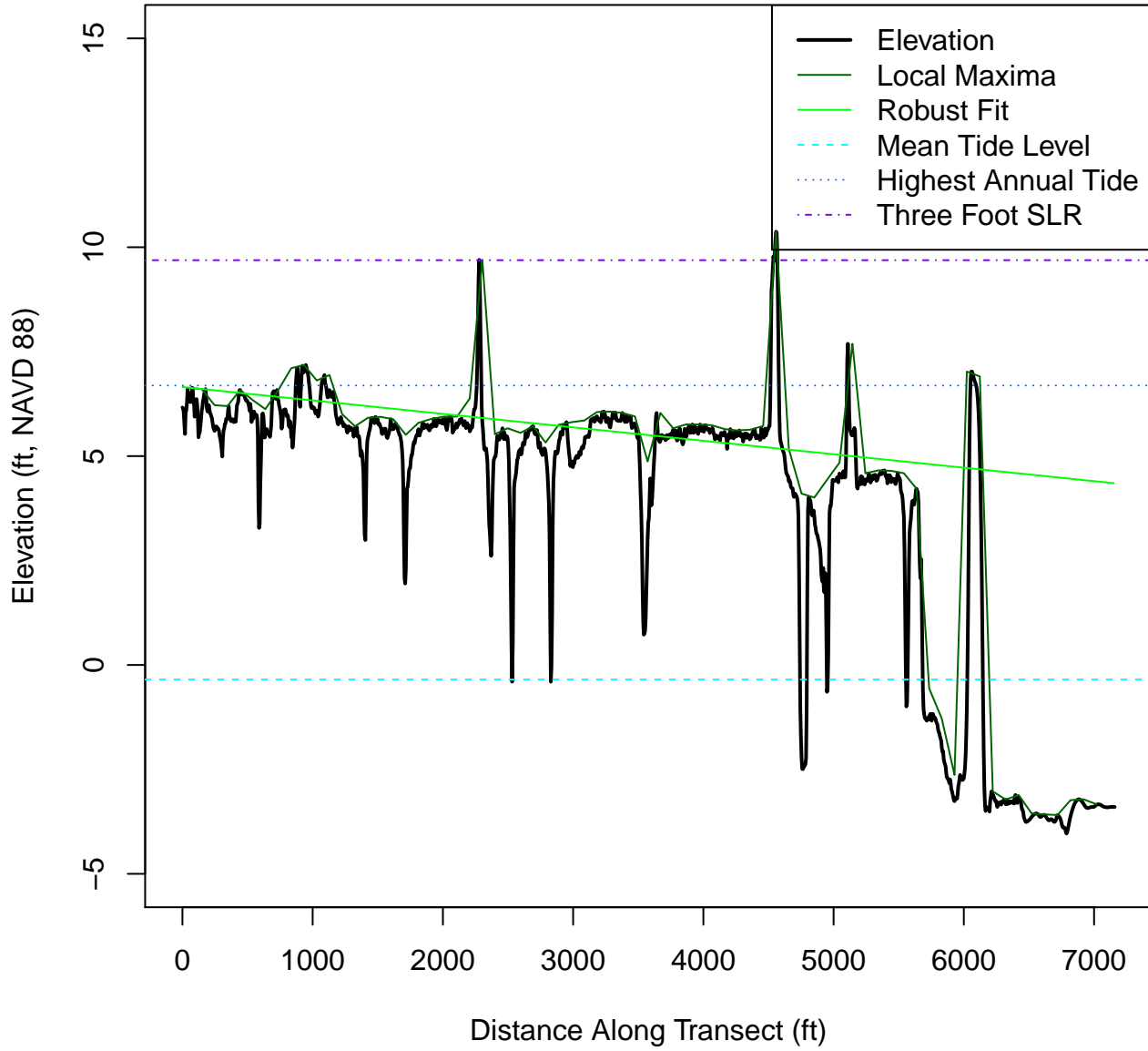
**Longitudinal Profile
TR15
Window = 20**



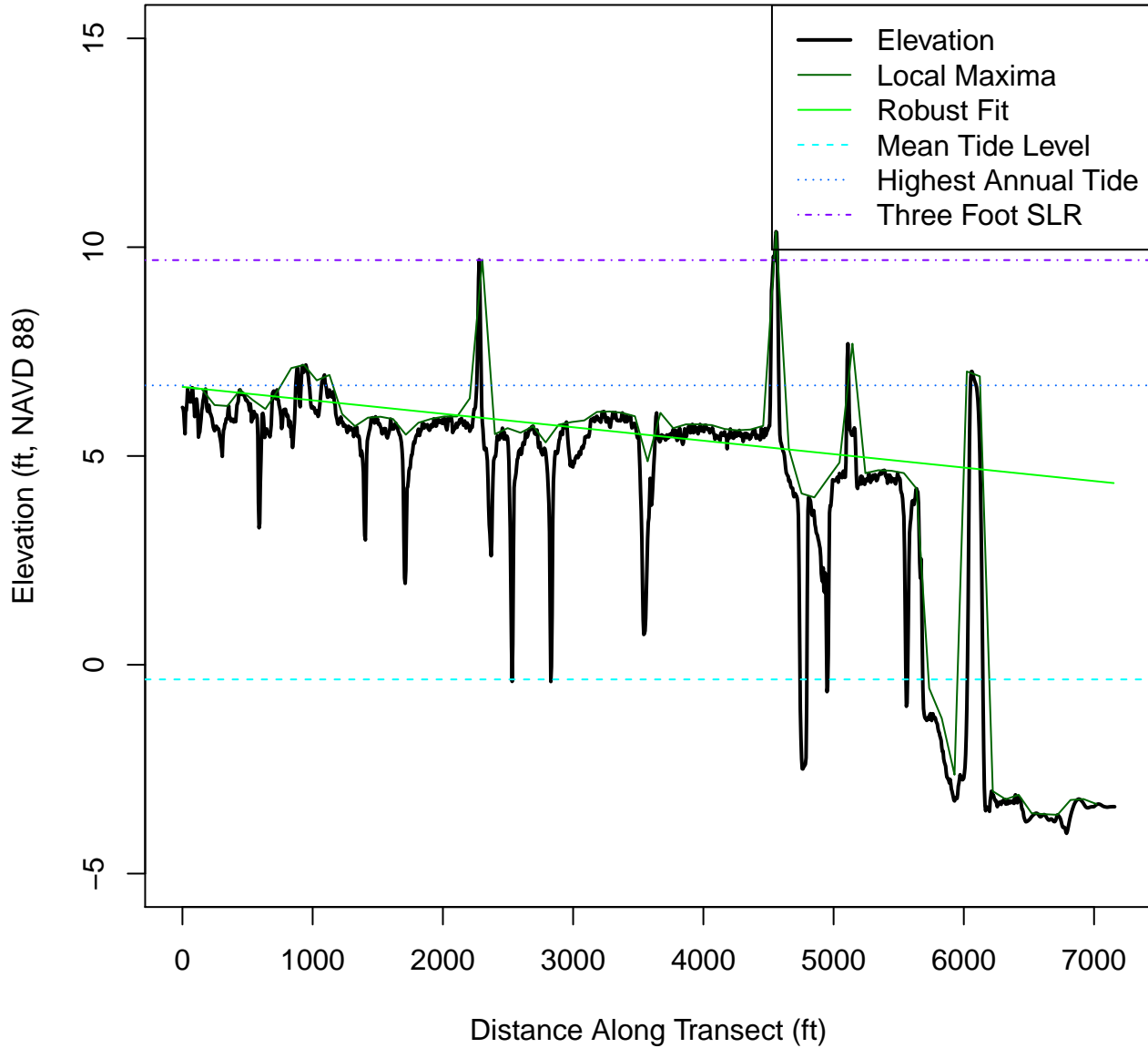
**Longitudinal Profile
TR16
Window = 20**



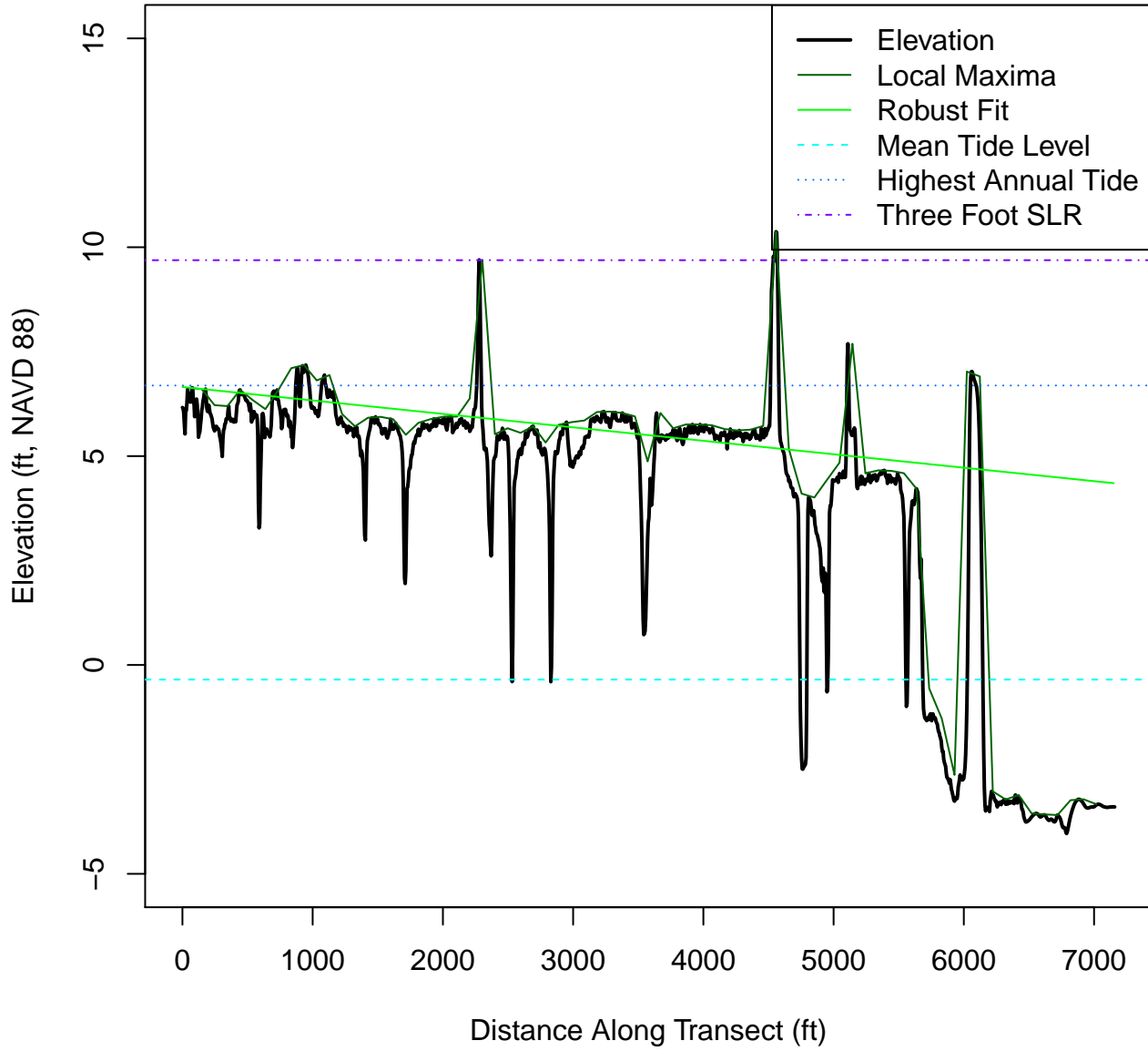
**Longitudinal Profile
TR17
Window = 20**



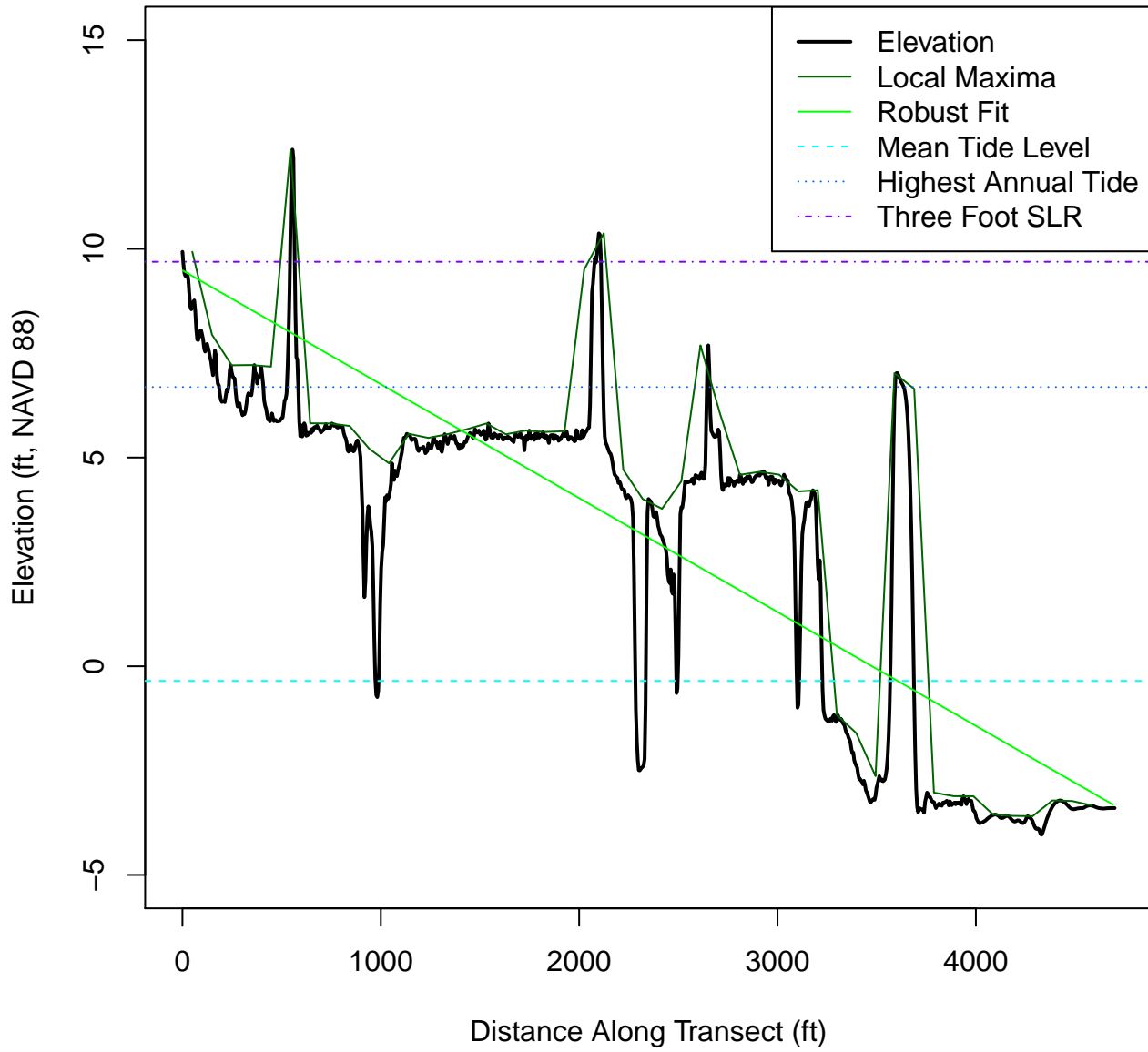
**Longitudinal Profile
TR18
Window = 20**



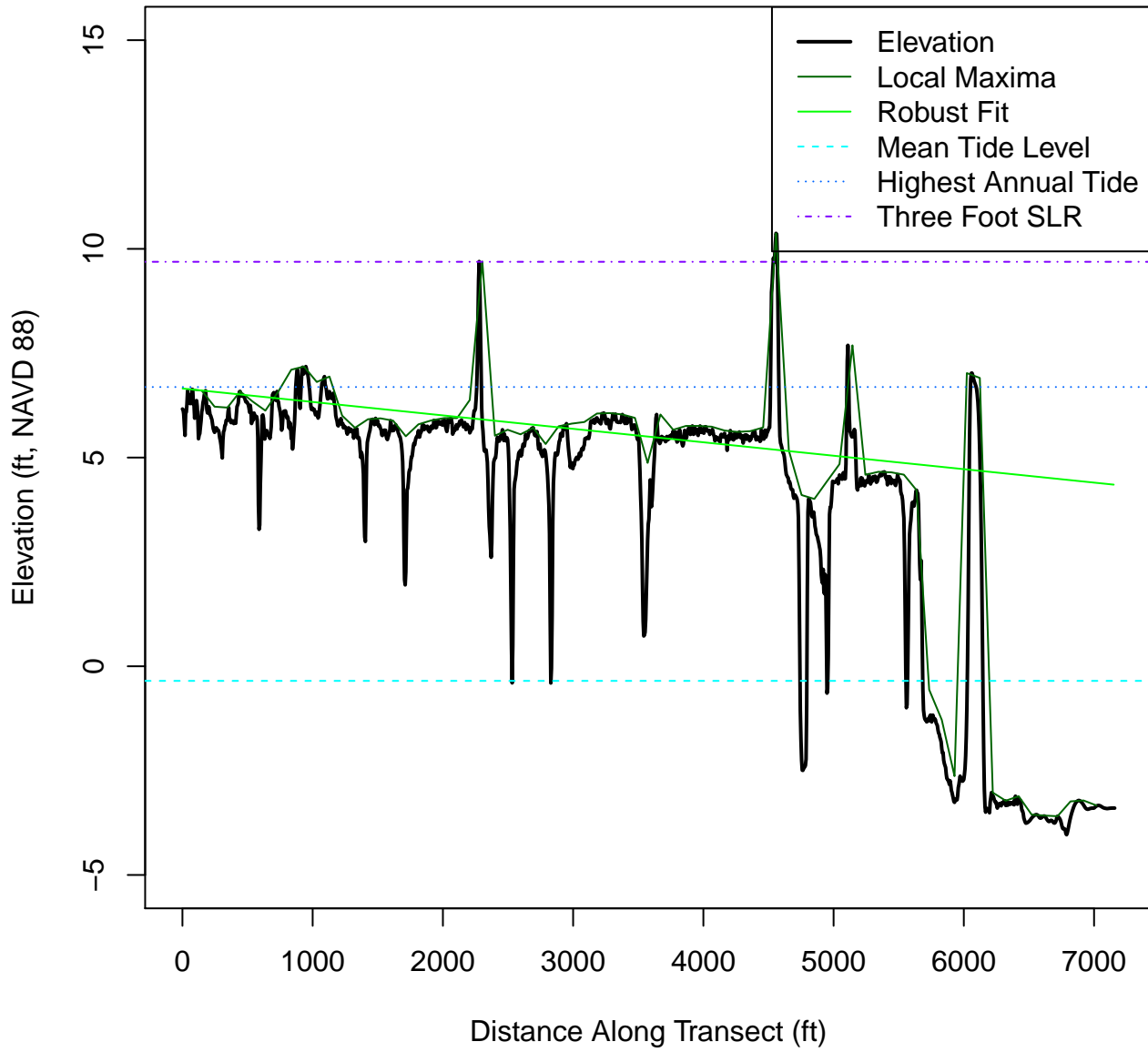
**Longitudinal Profile
TR19
Window = 20**



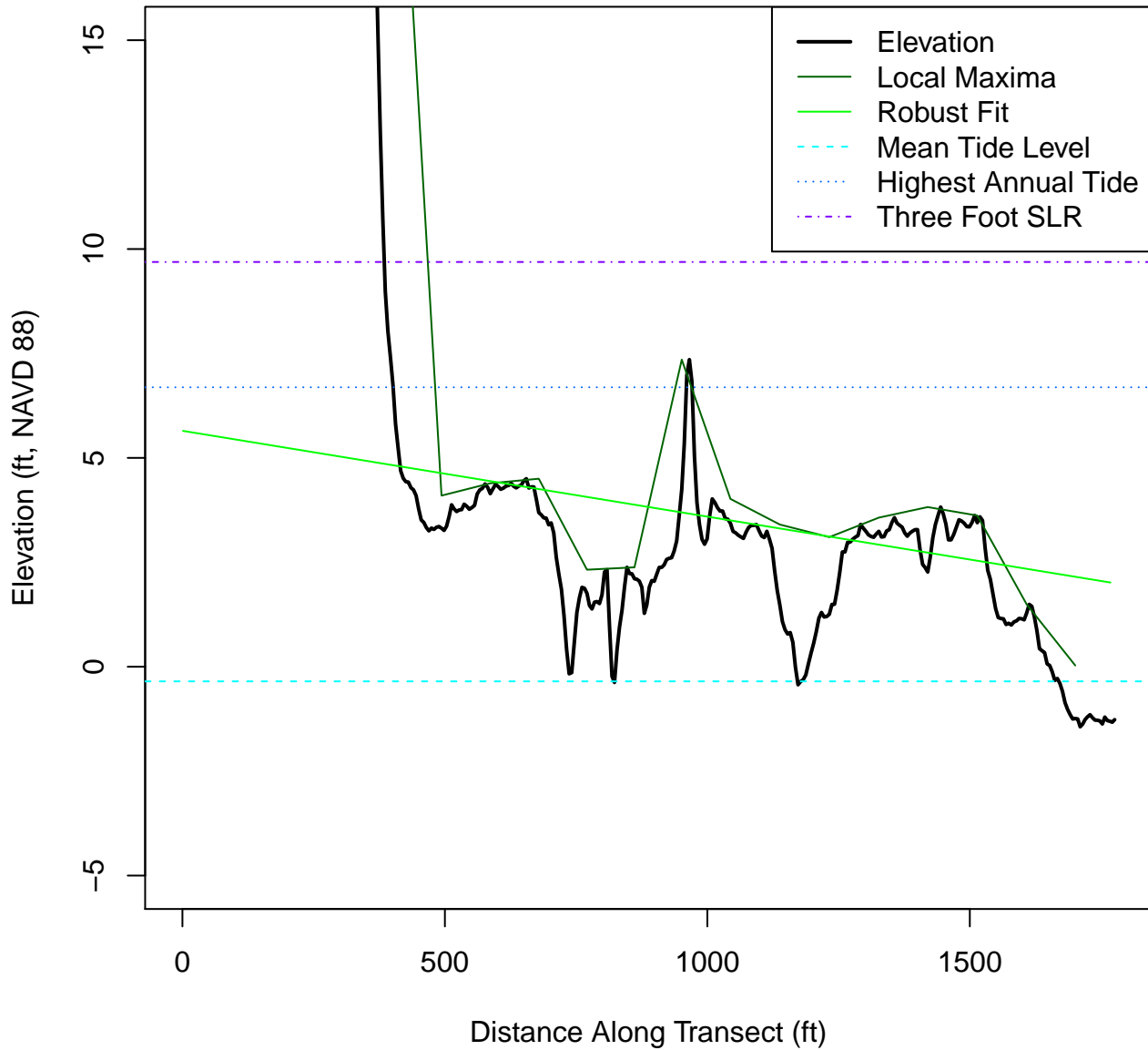
**Longitudinal Profile
TR20
Window = 20**



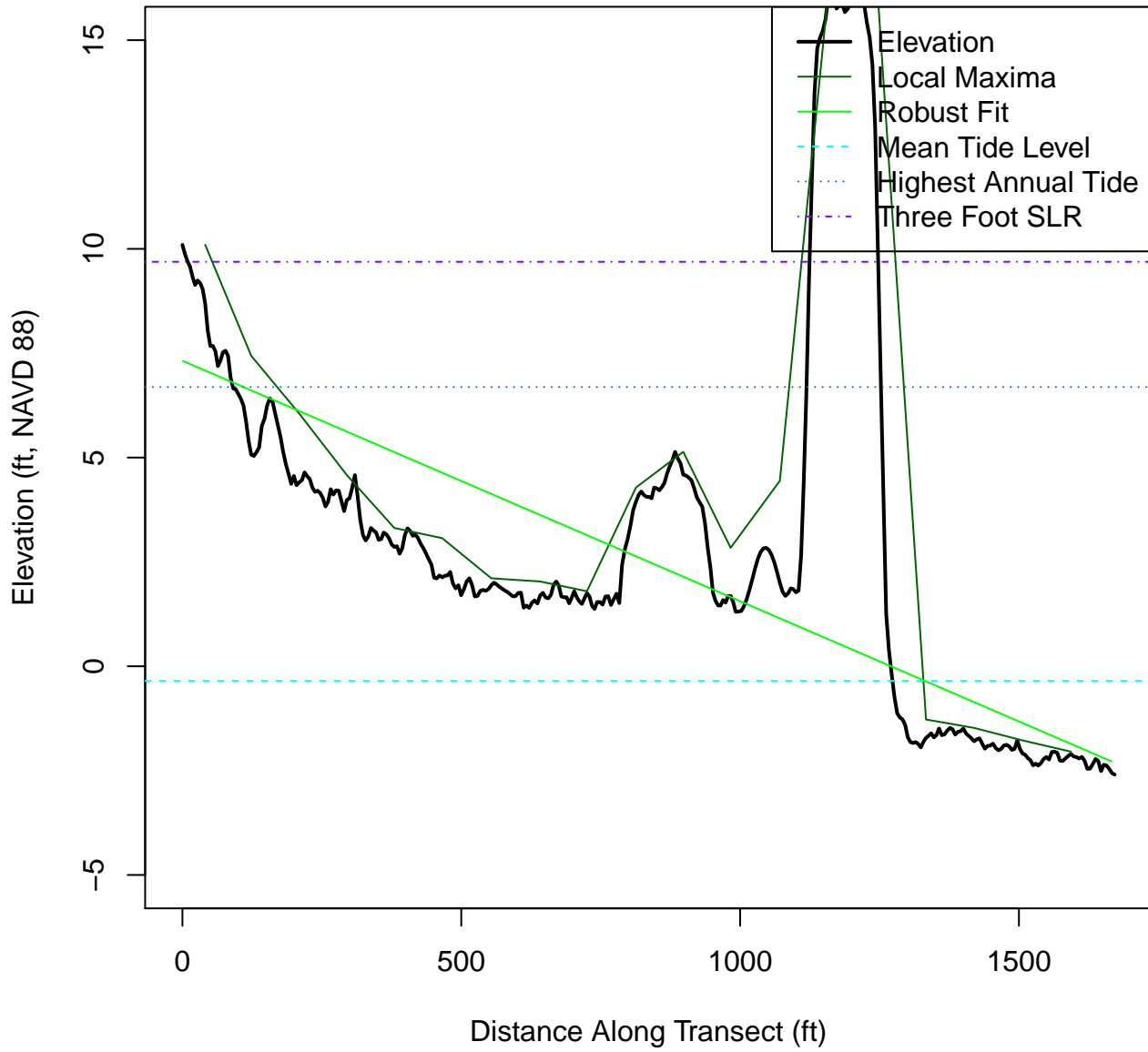
**Longitudinal Profile
TR21
Window = 20**



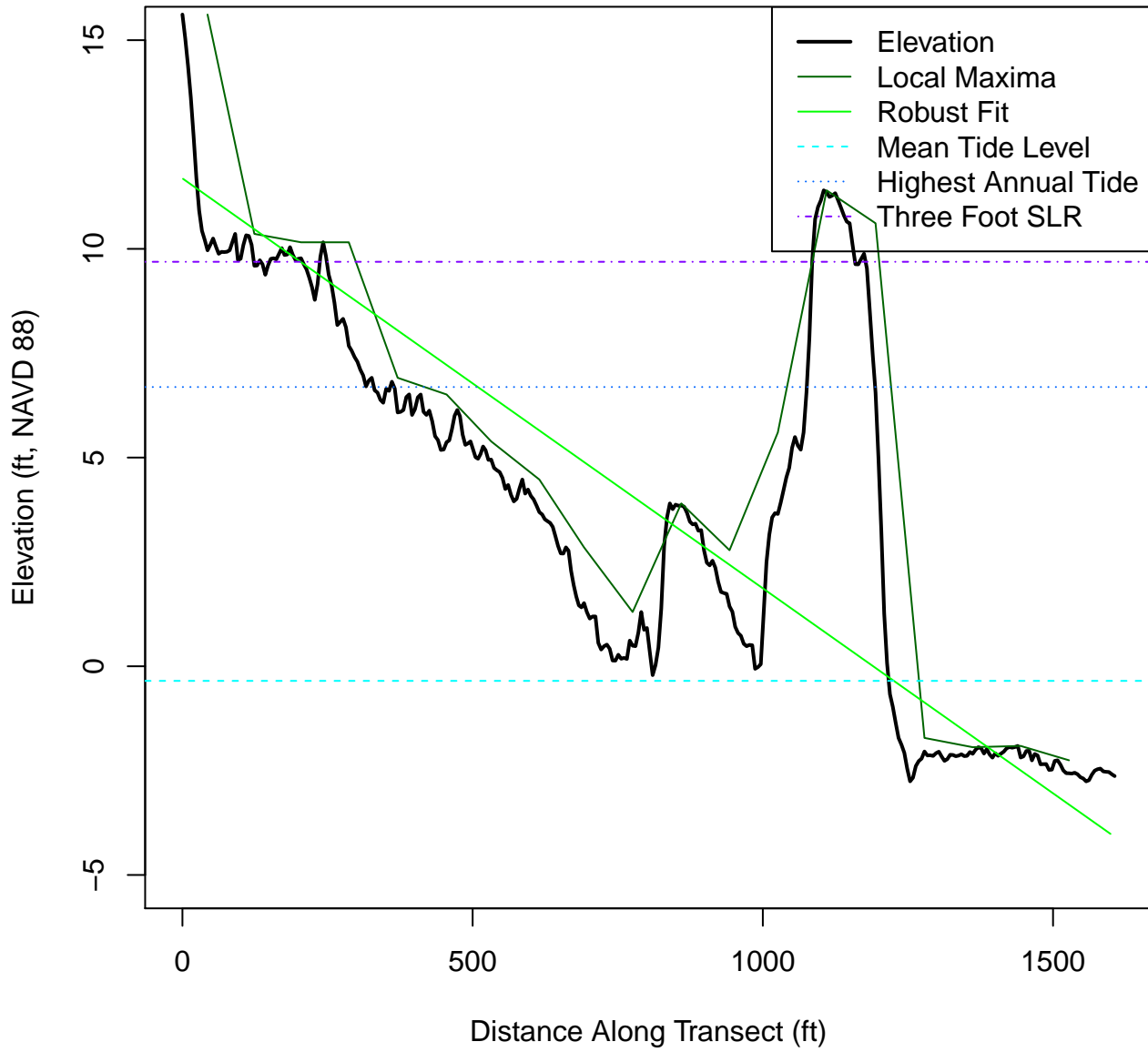
**Longitudinal Profile
TR22
Window = 19**



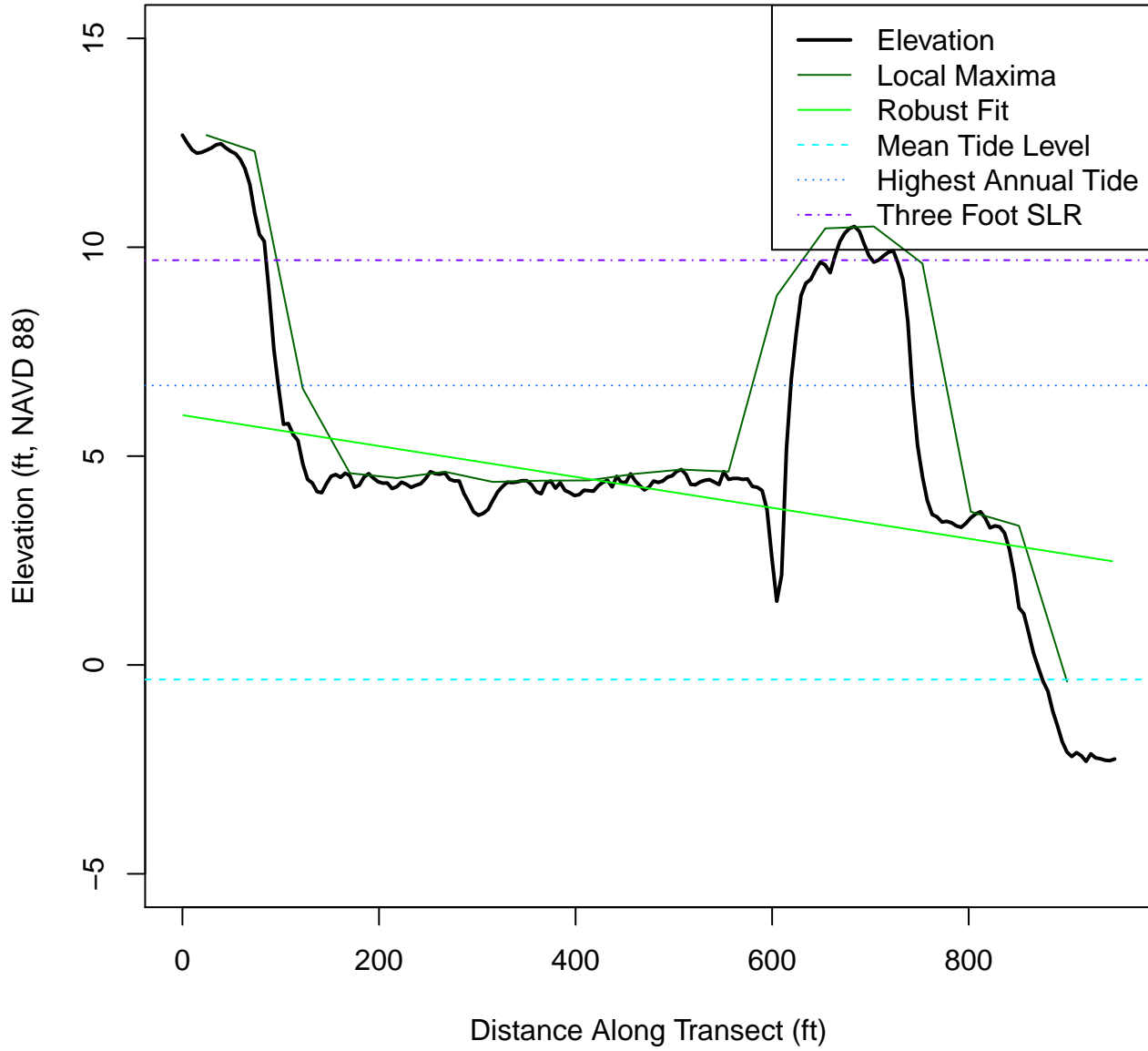
**Longitudinal Profile
TR23
Window = 18**



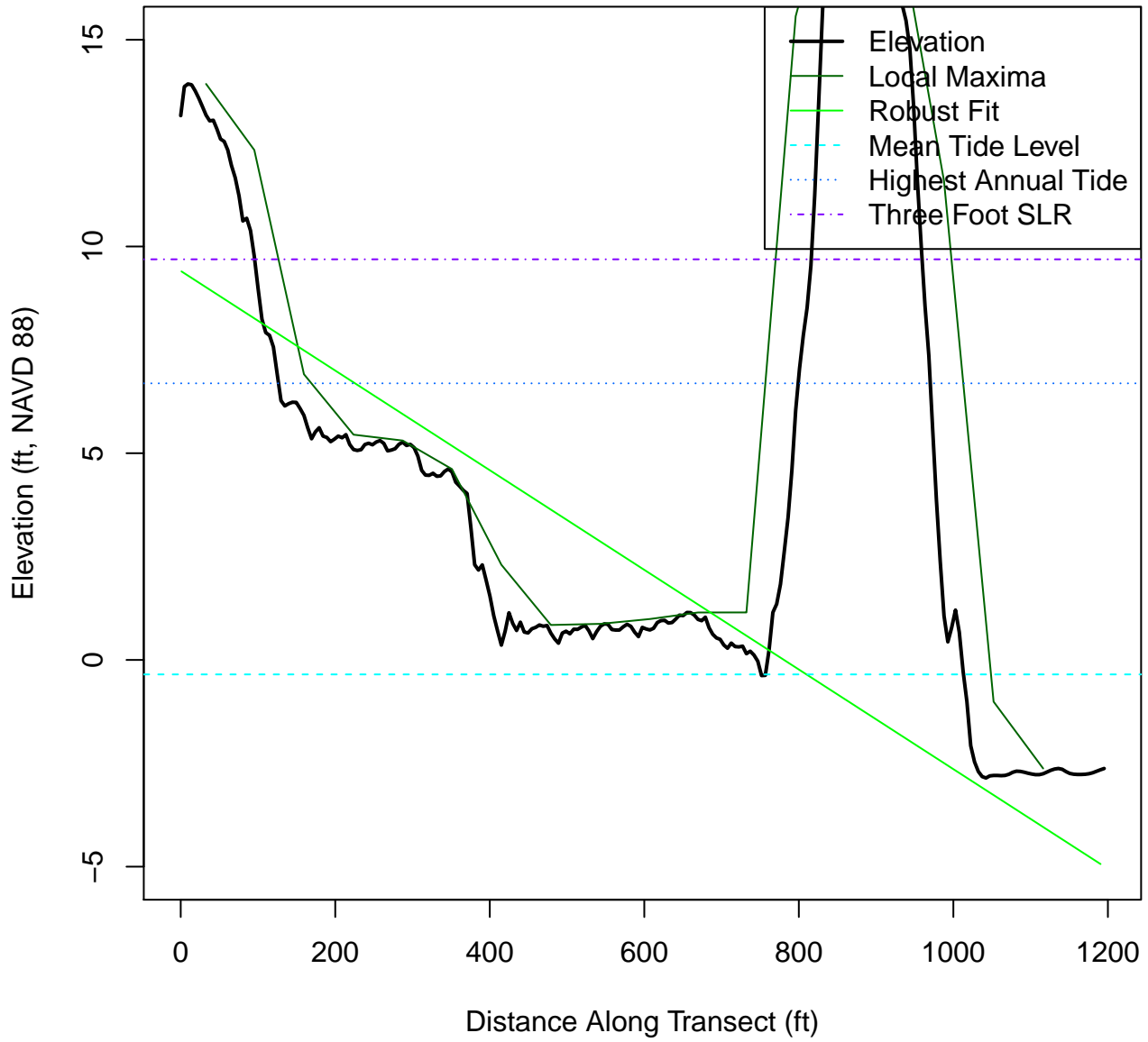
**Longitudinal Profile
TR24
Window = 17**



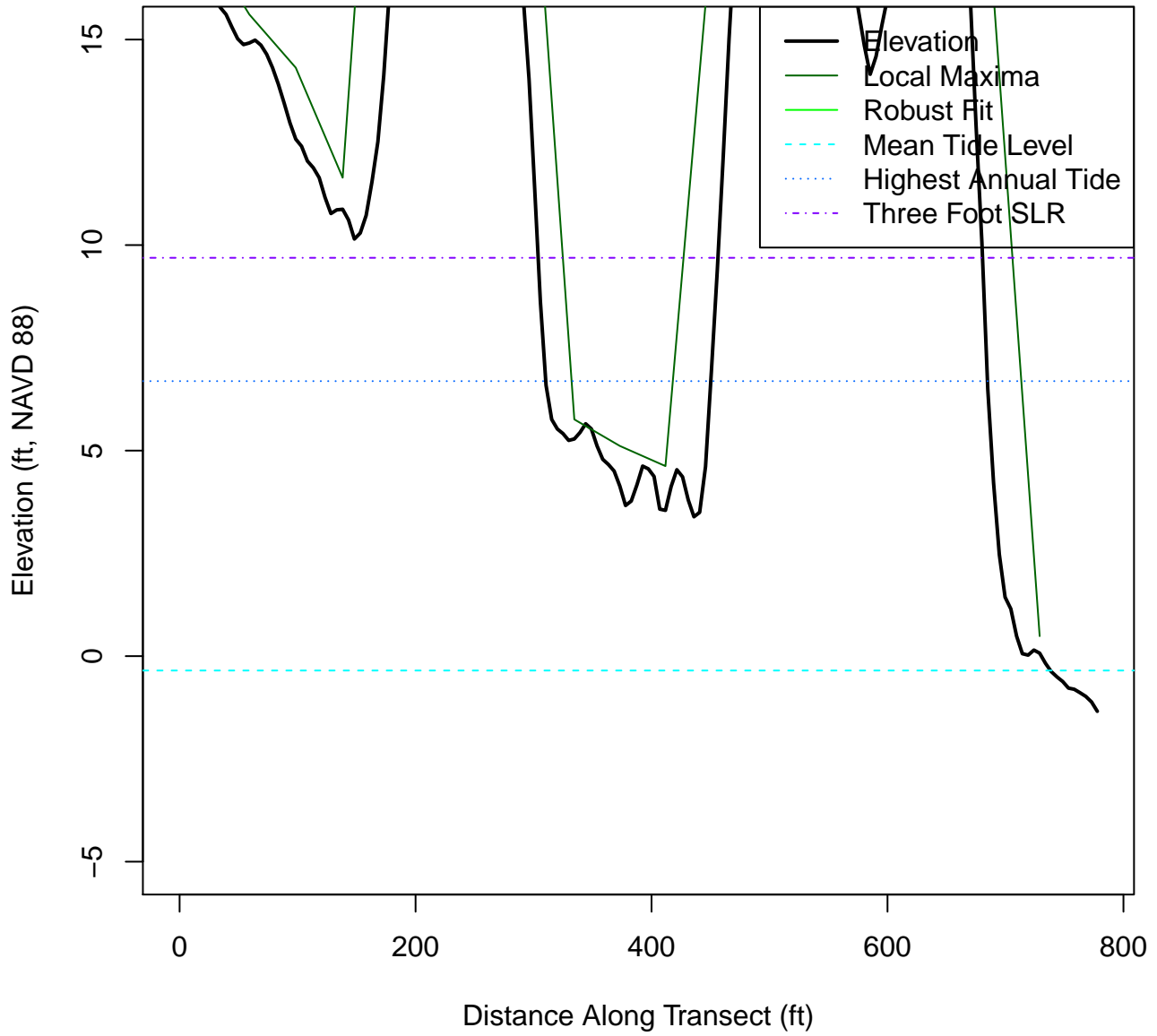
**Longitudinal Profile
TR25
Window = 10**



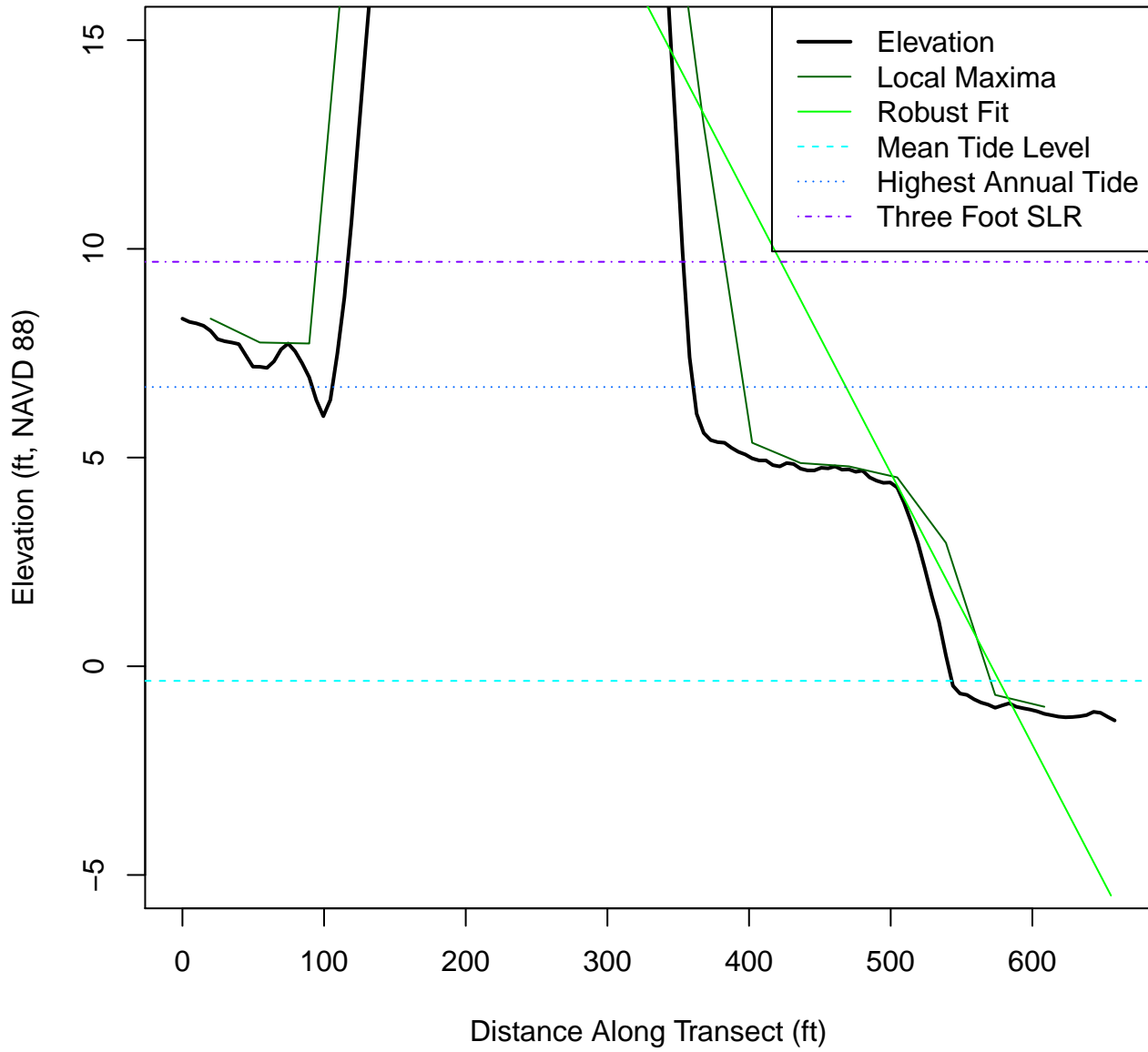
**Longitudinal Profile
TR26
Window = 13**



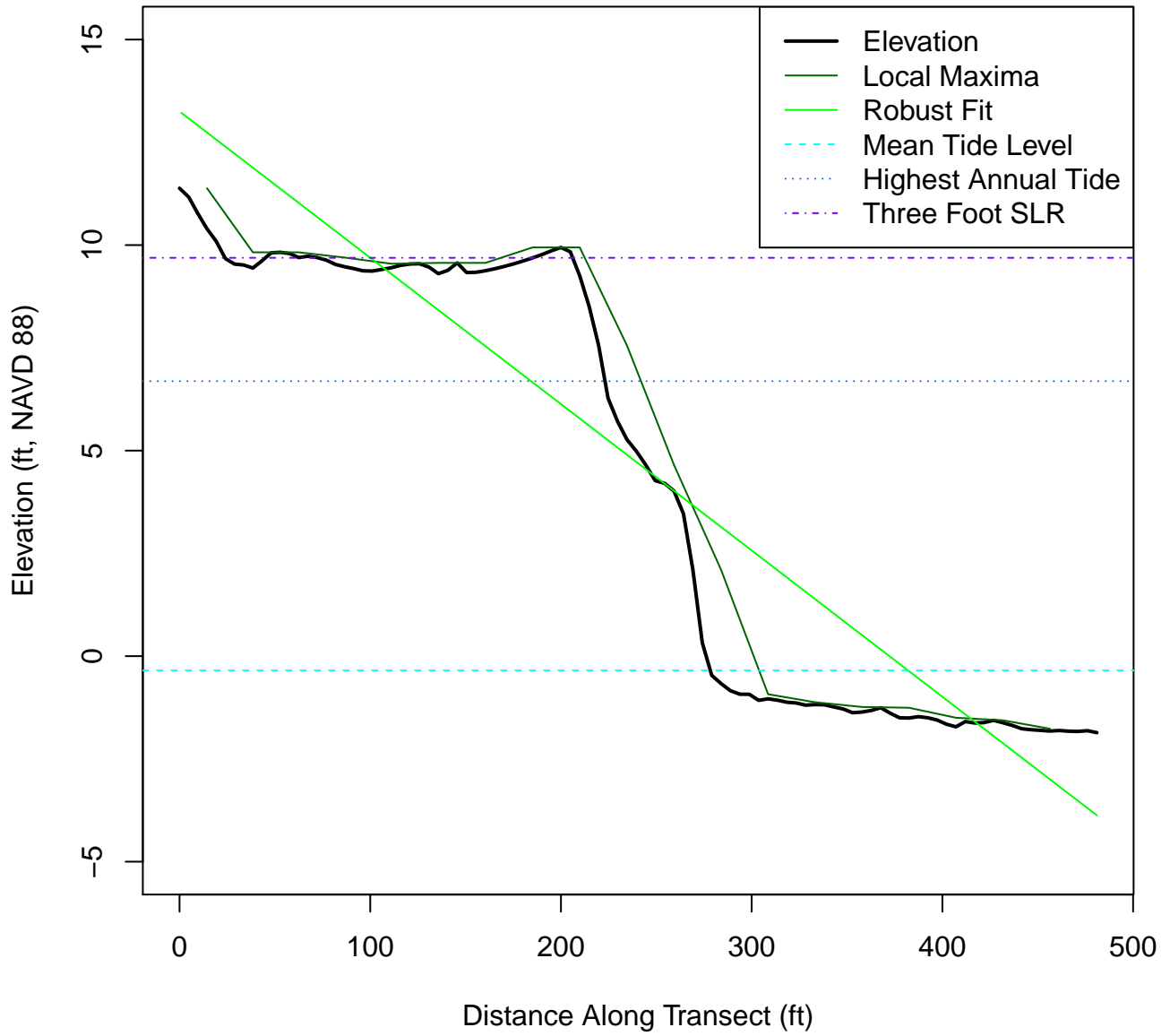
**Longitudinal Profile
TR27
Window = 8**



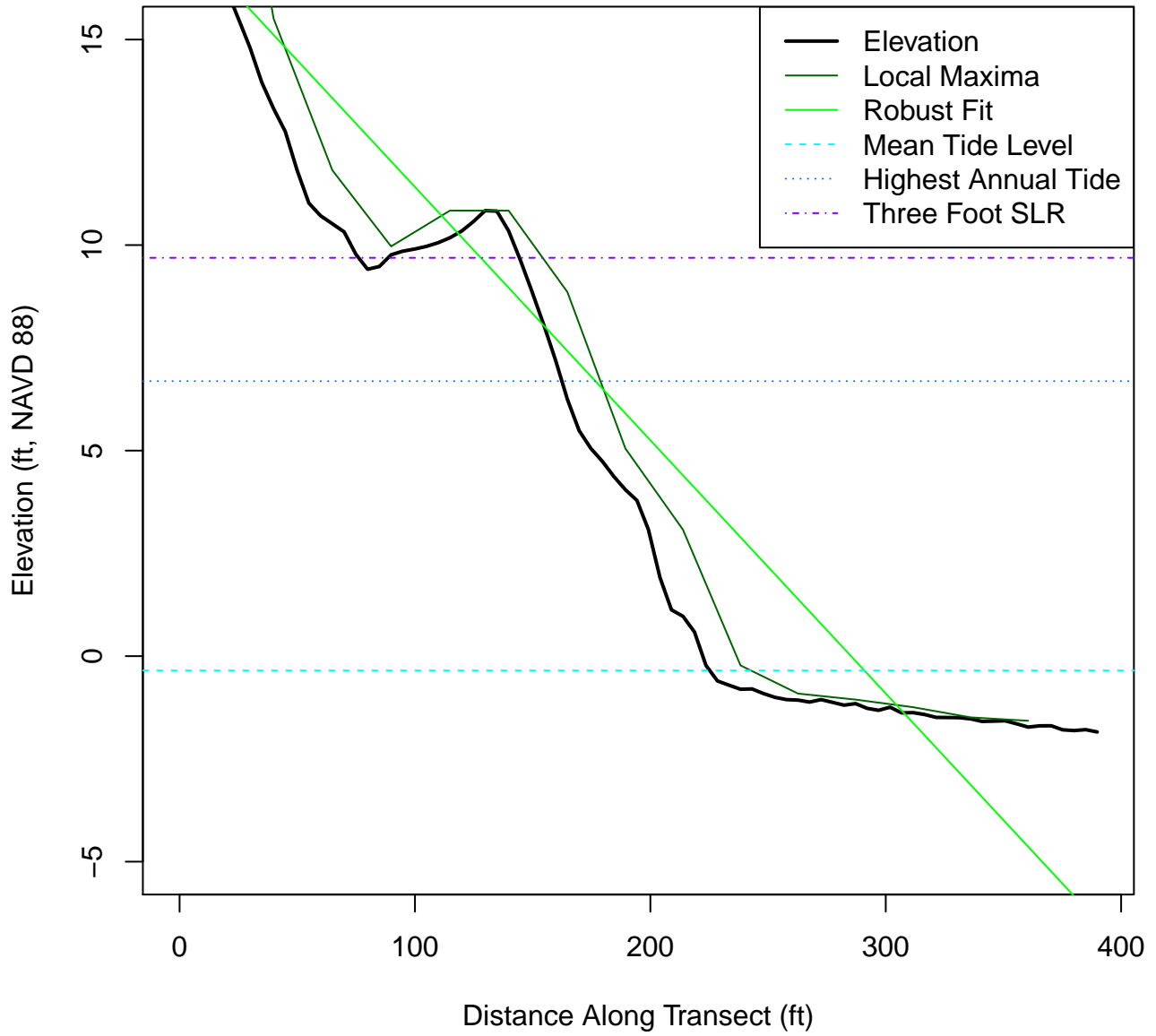
**Longitudinal Profile
TR28
Window = 7**



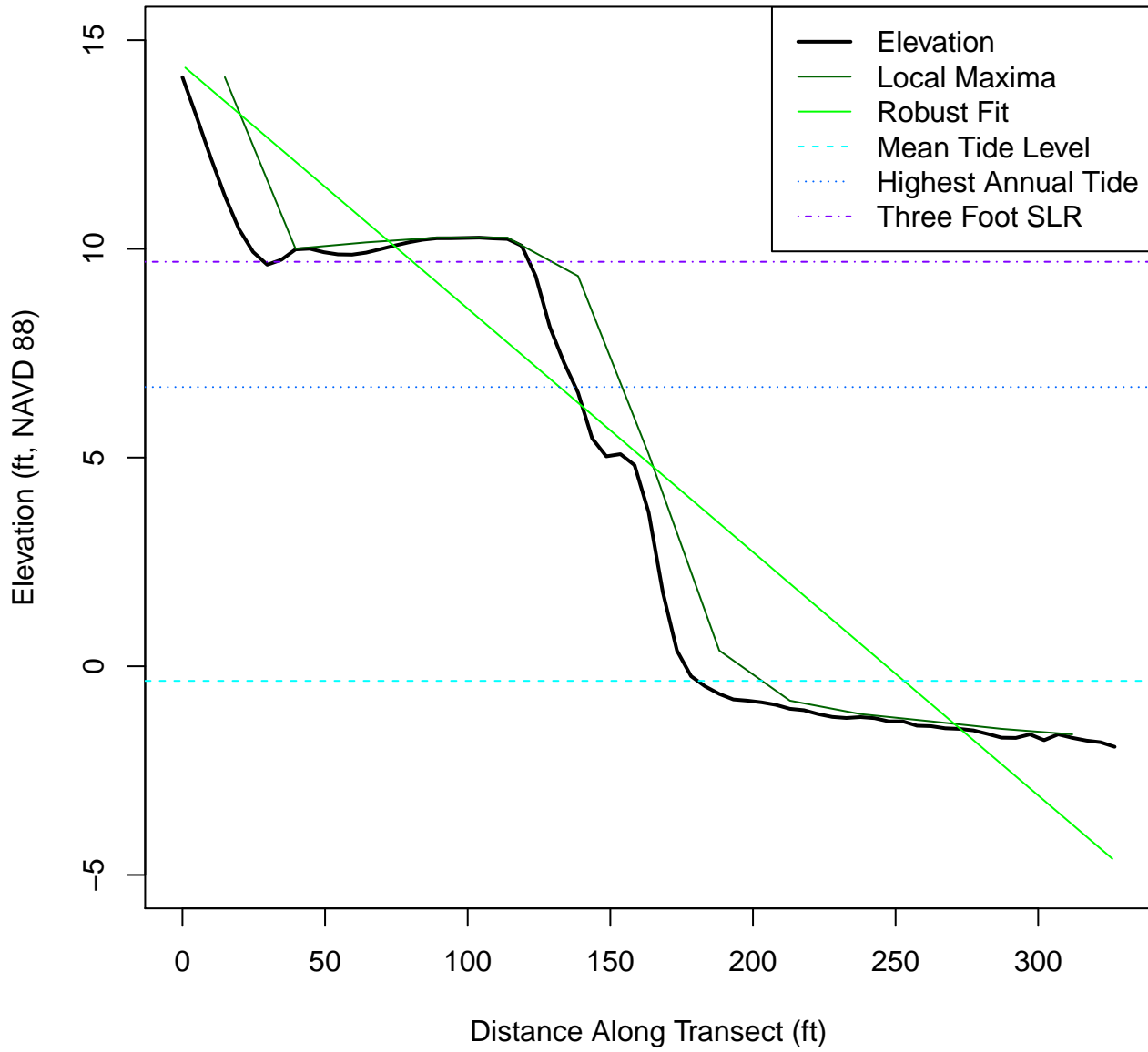
**Longitudinal Profile
TR29
Window = 5**



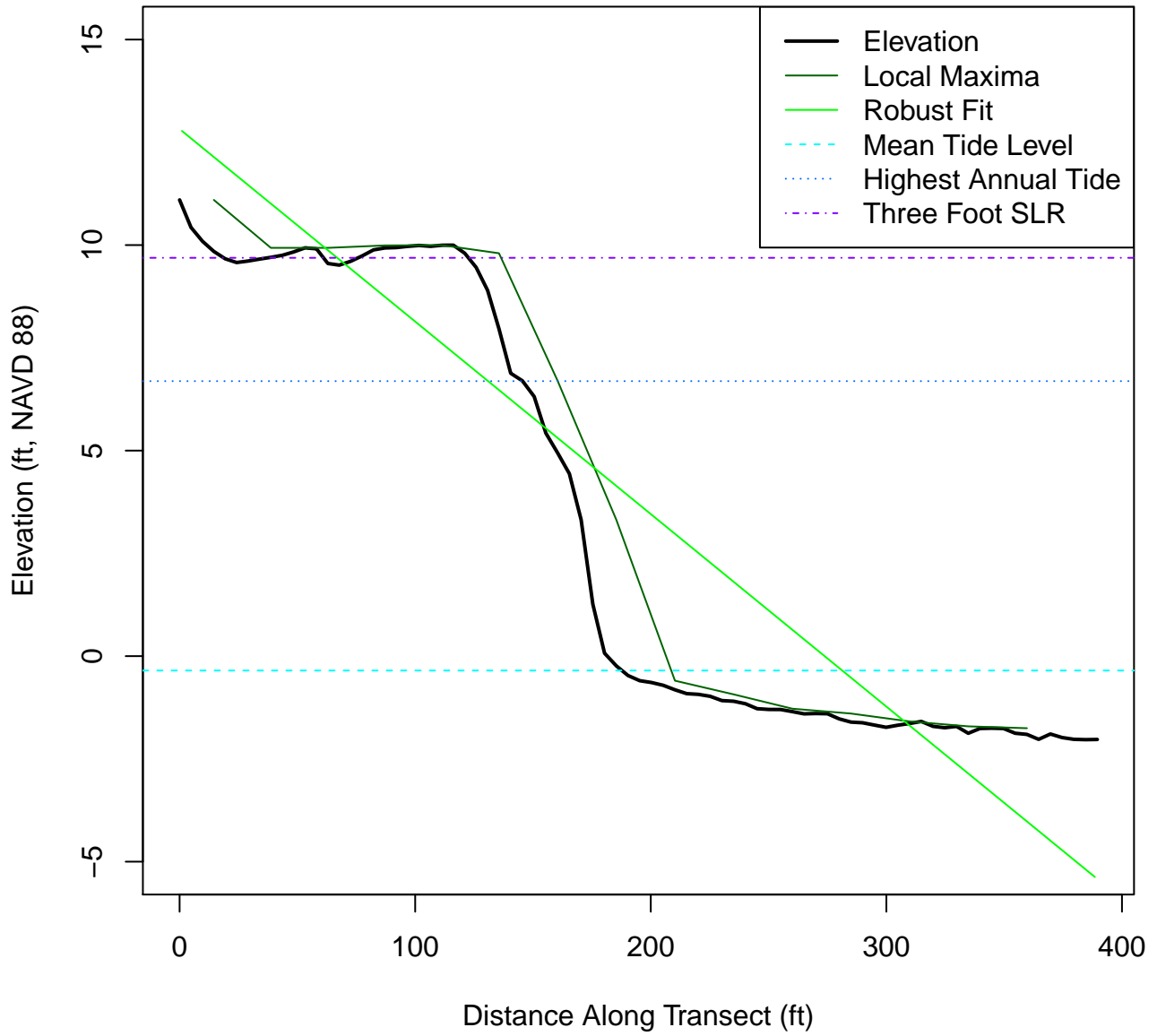
**Longitudinal Profile
TR30
Window = 5**



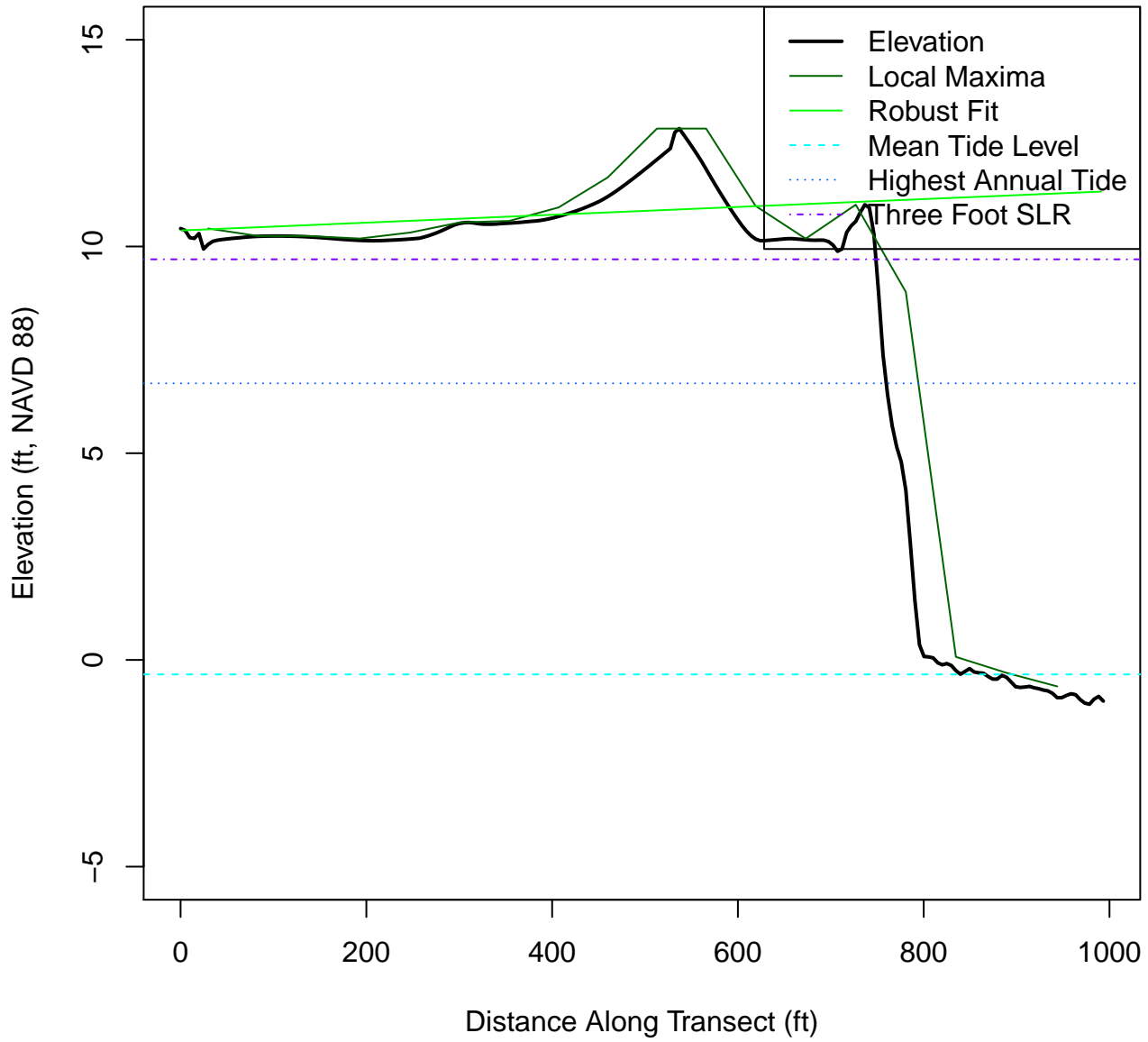
**Longitudinal Profile
TR31
Window = 5**



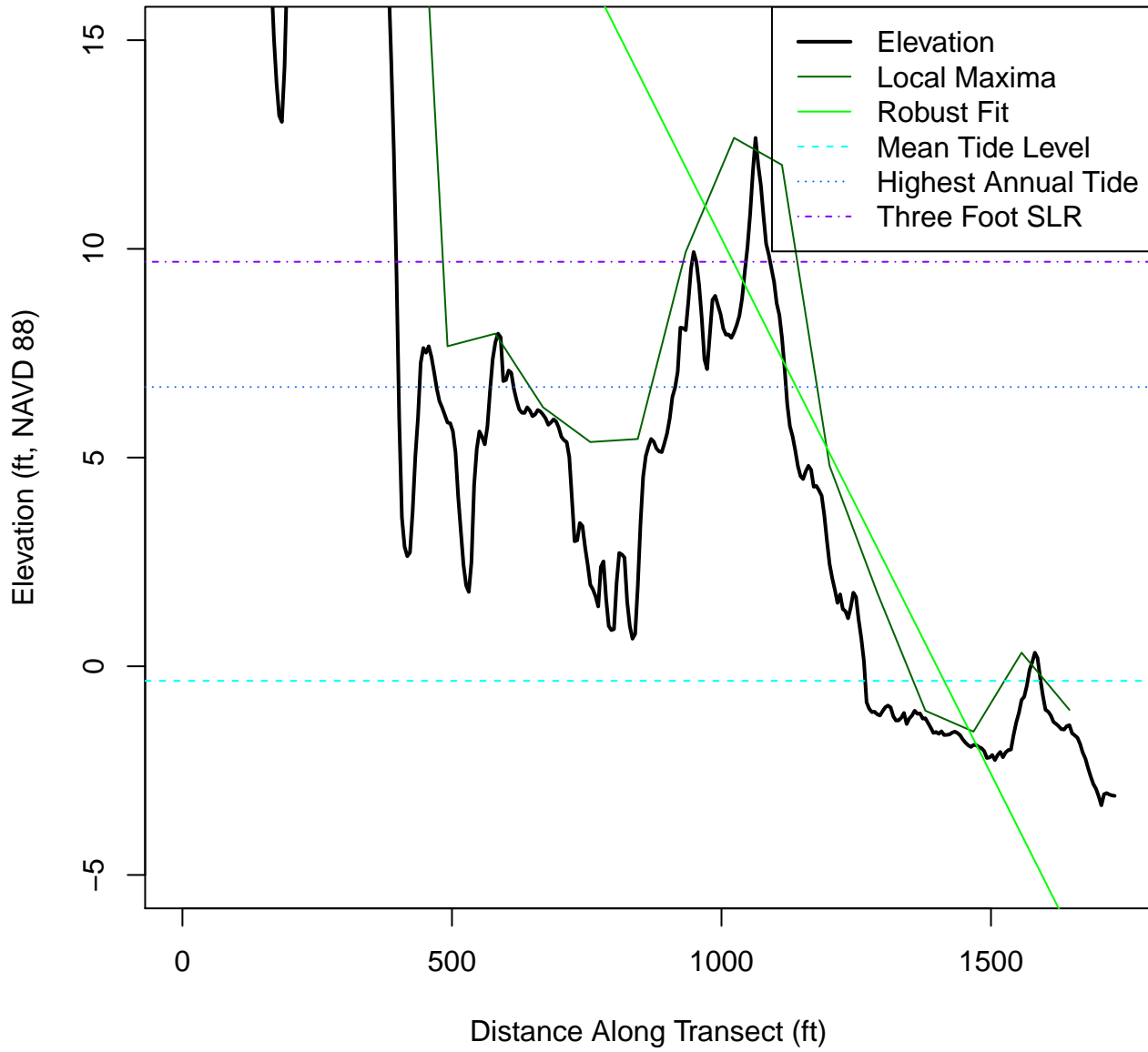
**Longitudinal Profile
TR32
Window = 5**



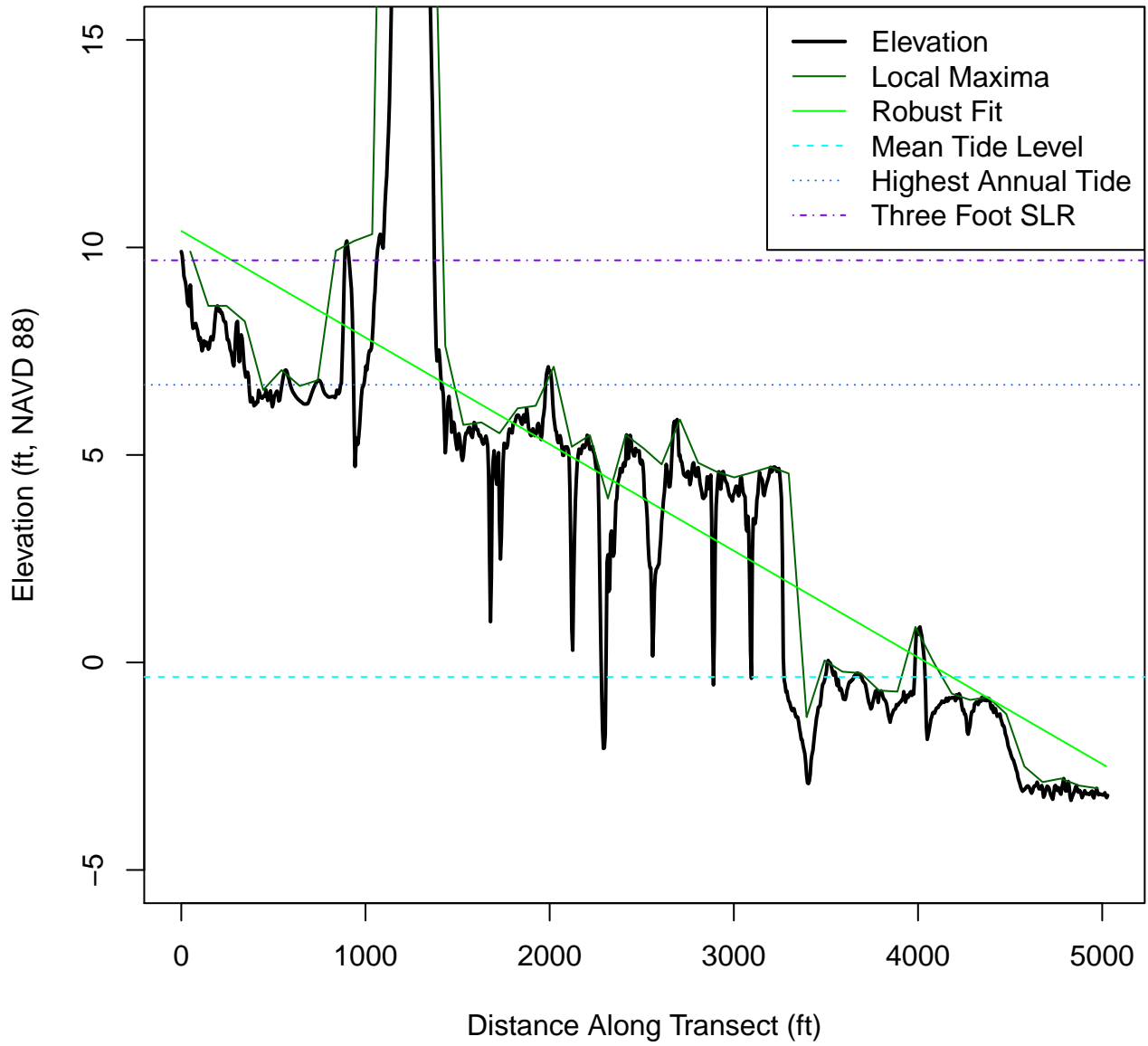
**Longitudinal Profile
TR33
Window = 11**



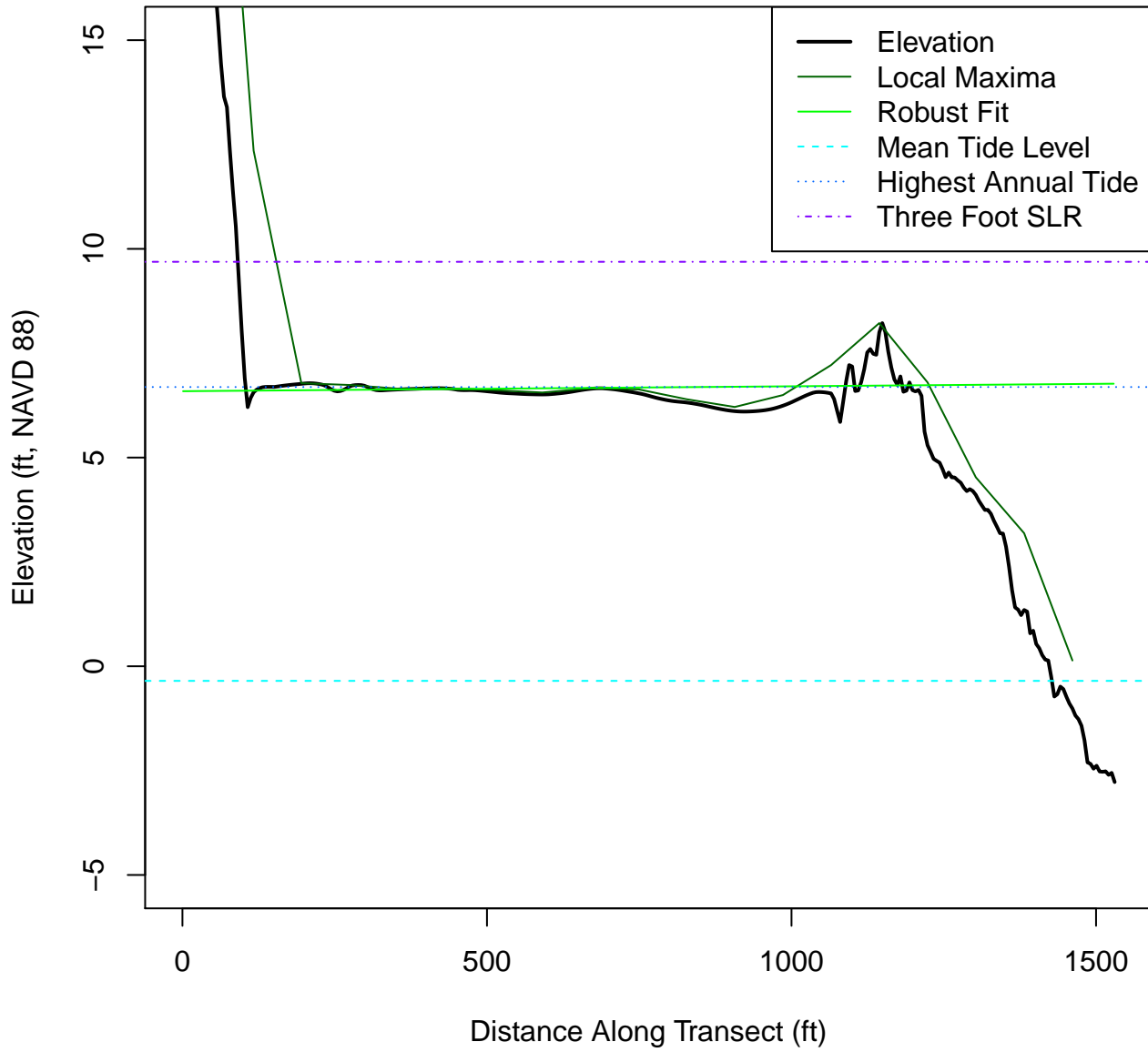
**Longitudinal Profile
TR34
Window = 18**



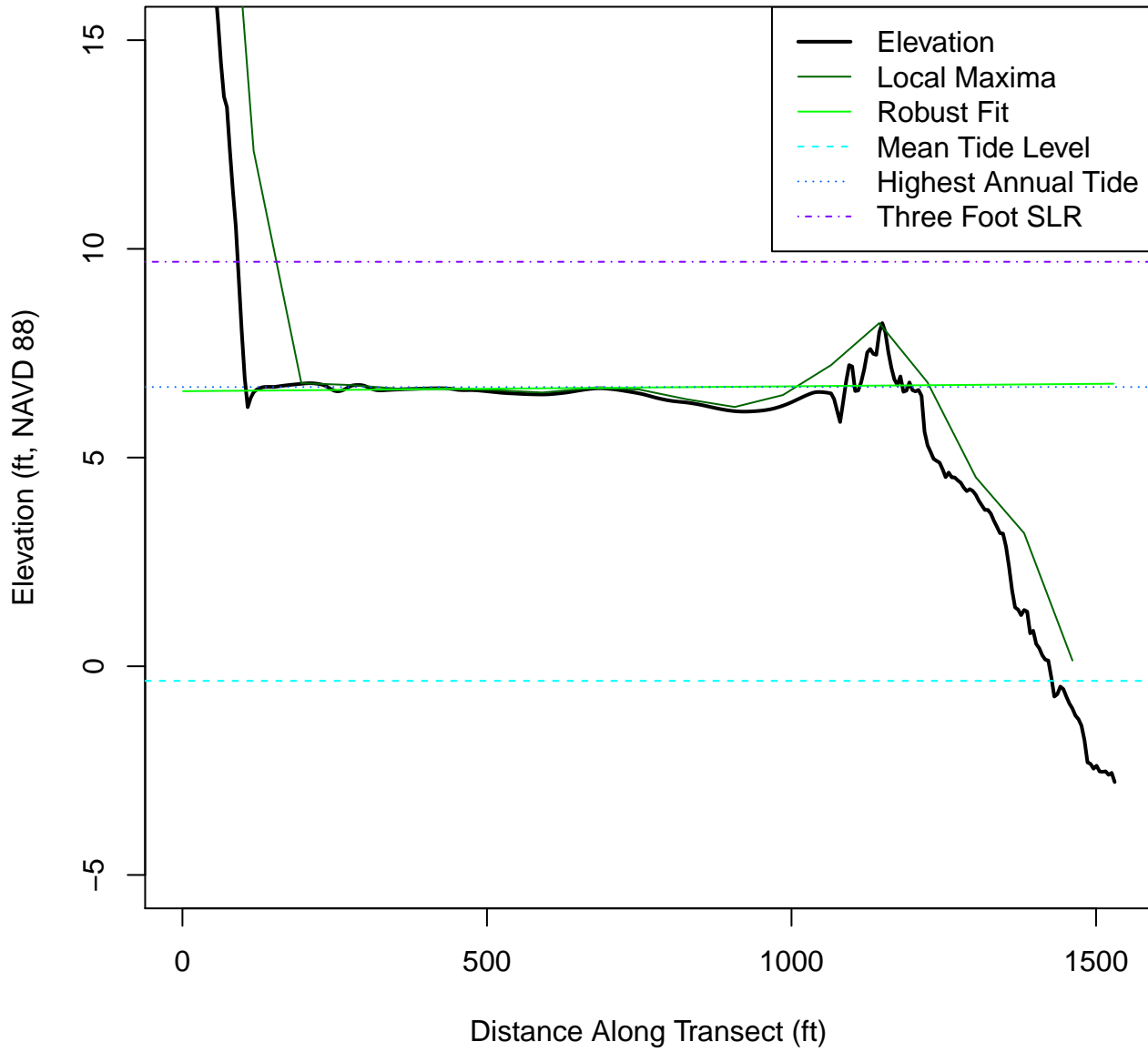
Longitudinal Profile TR35 Window = 20



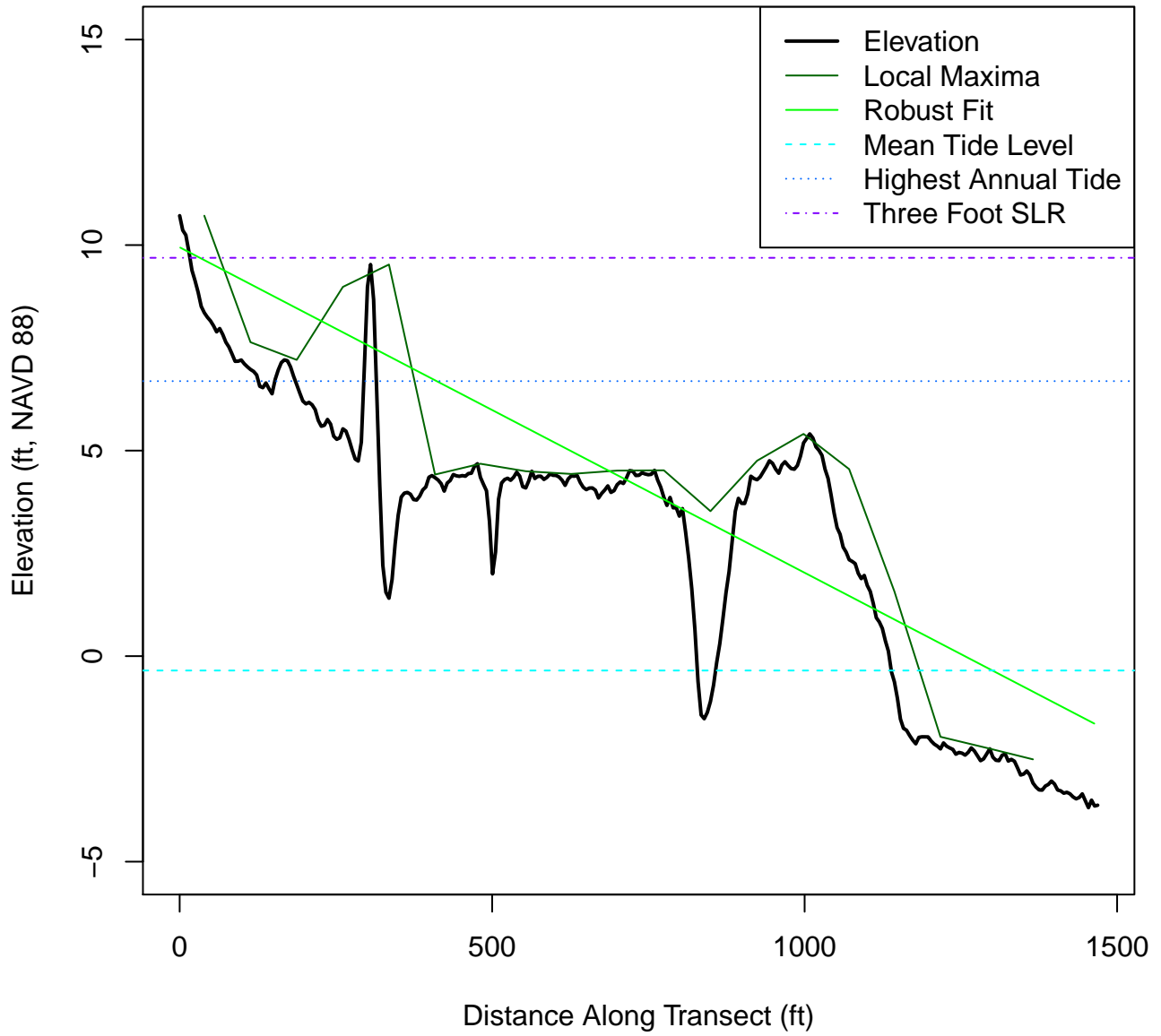
**Longitudinal Profile
TR36
Window = 16**



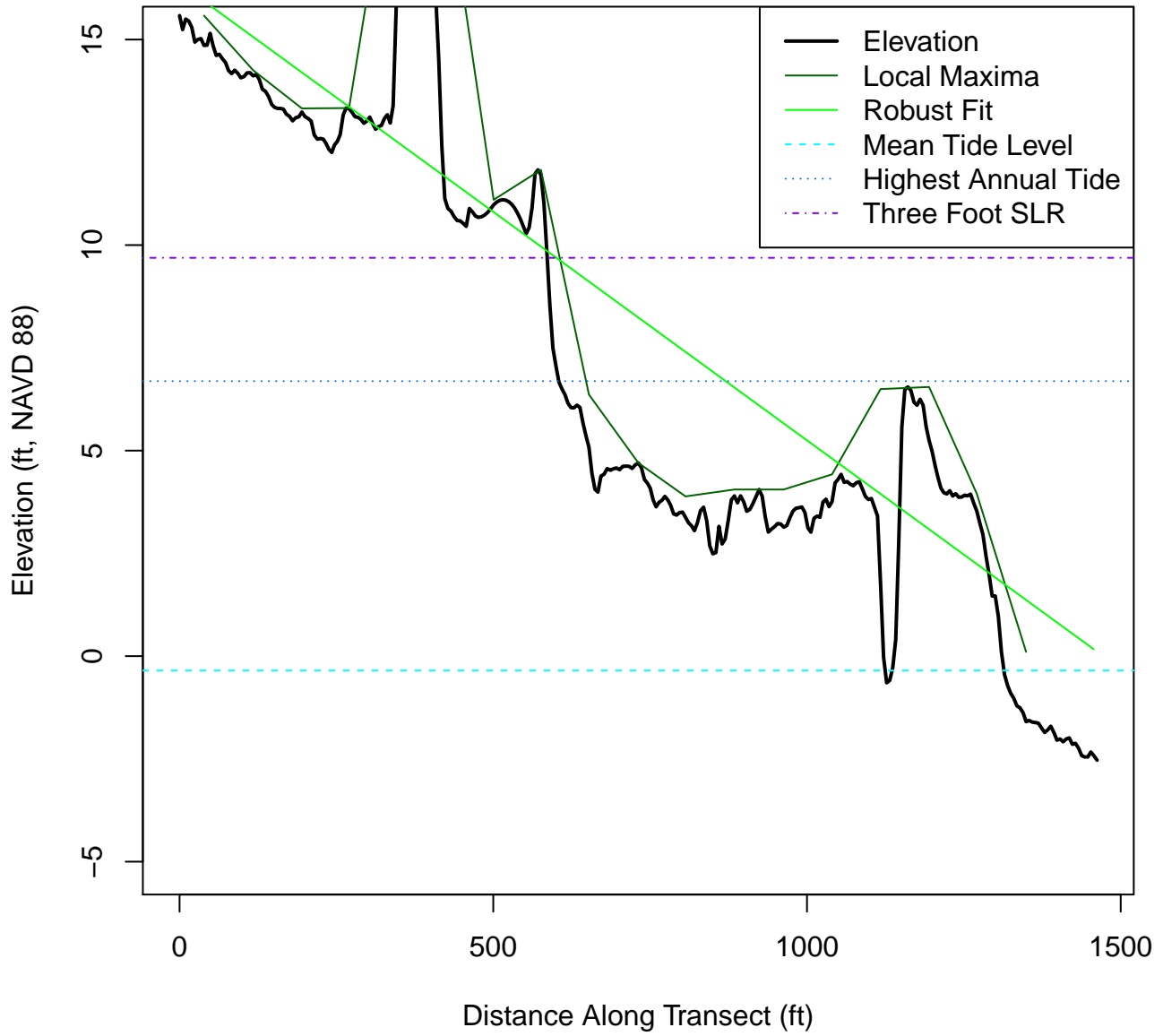
**Longitudinal Profile
TR37
Window = 16**



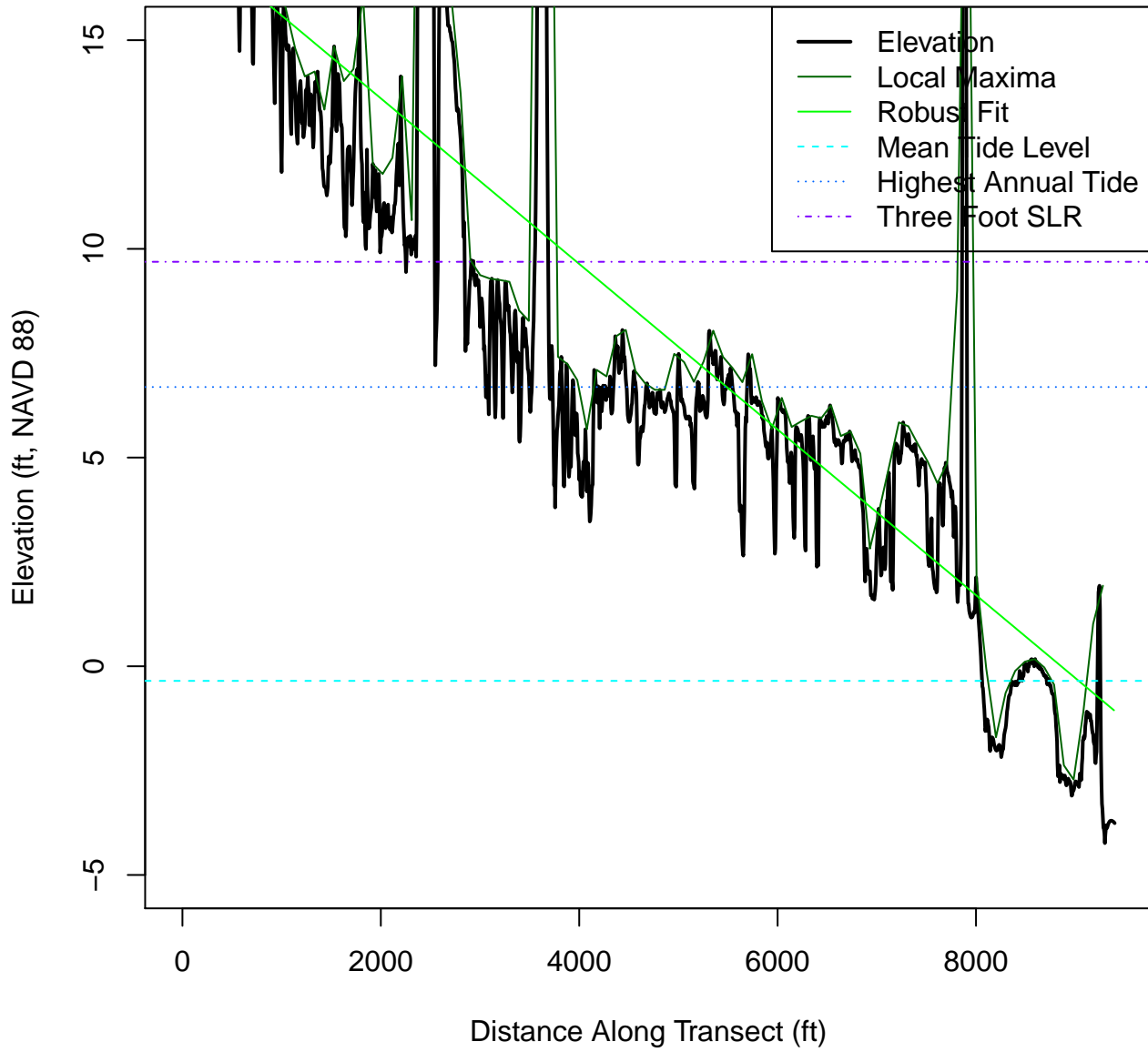
**Longitudinal Profile
TR38
Window = 15**



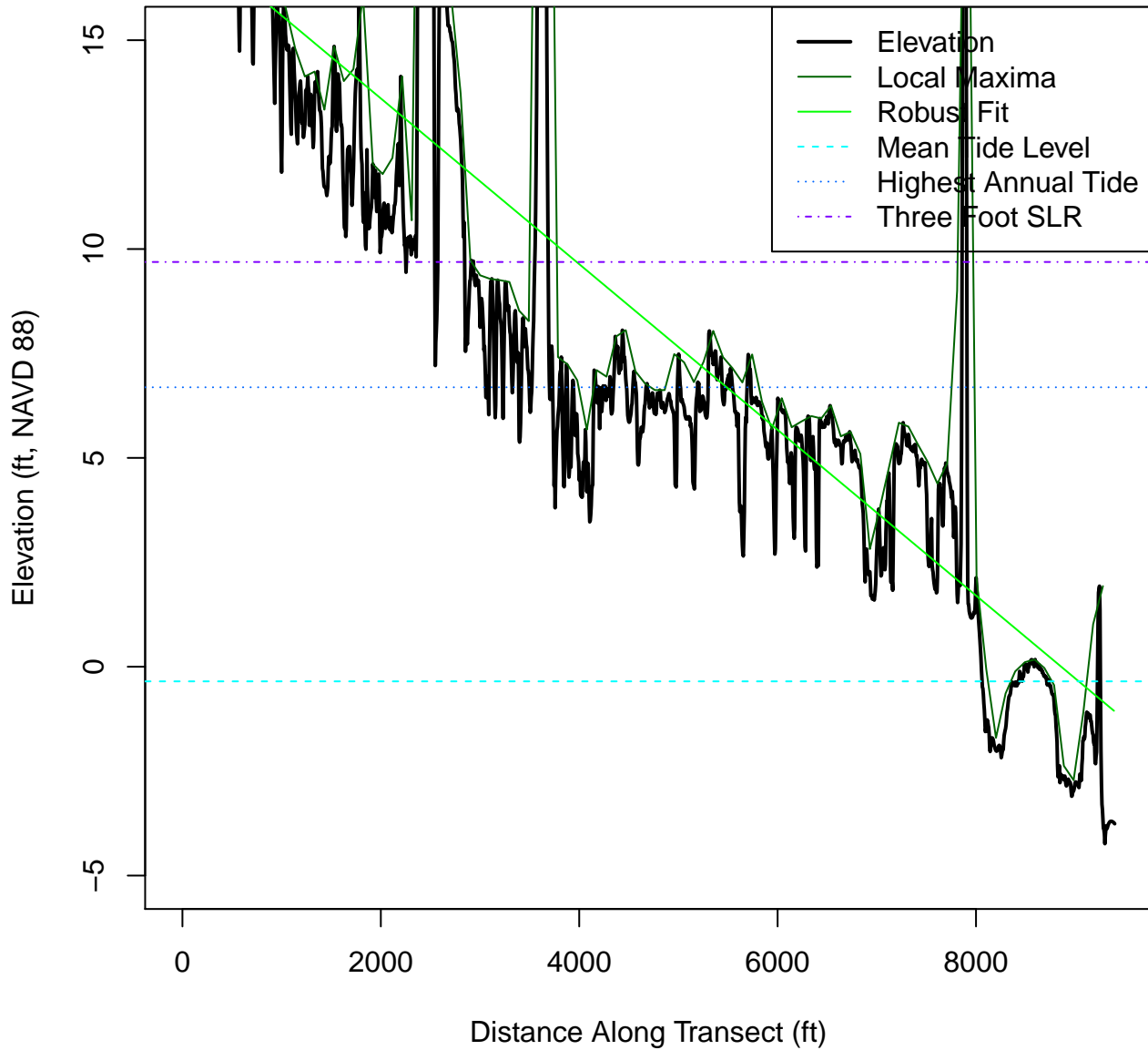
**Longitudinal Profile
TR39
Window = 16**



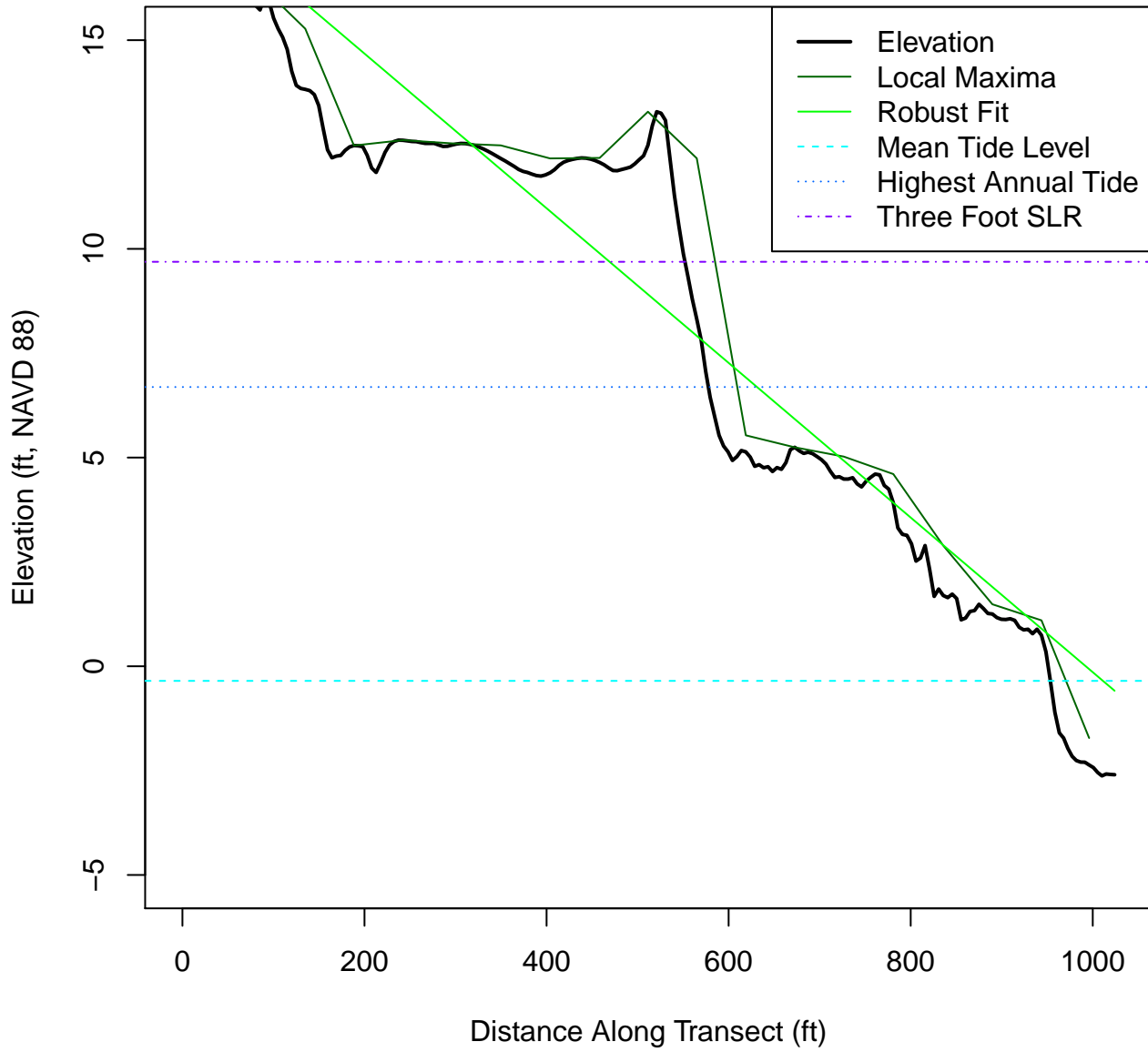
**Longitudinal Profile
TR40
Window = 20**



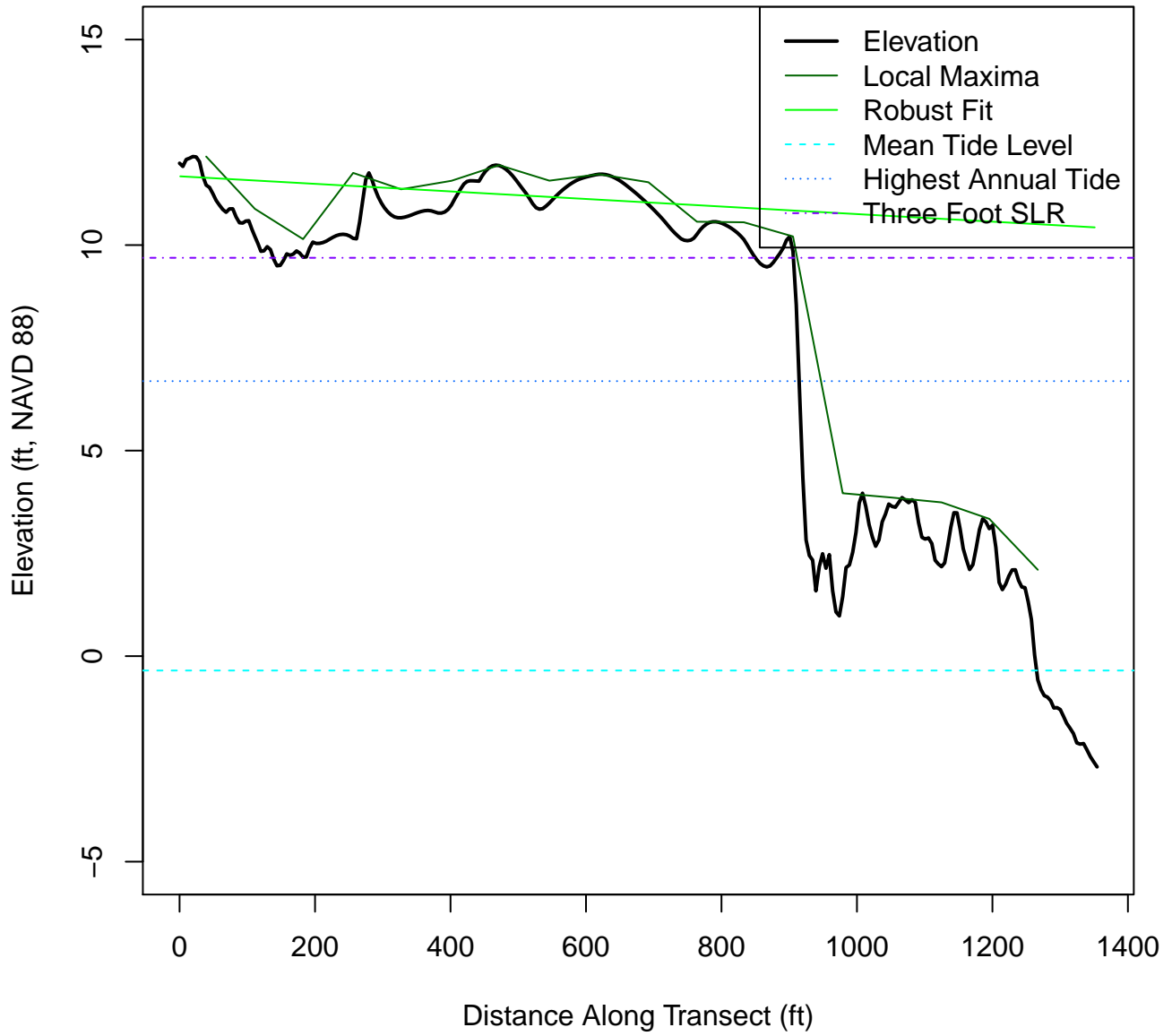
**Longitudinal Profile
TR41
Window = 20**



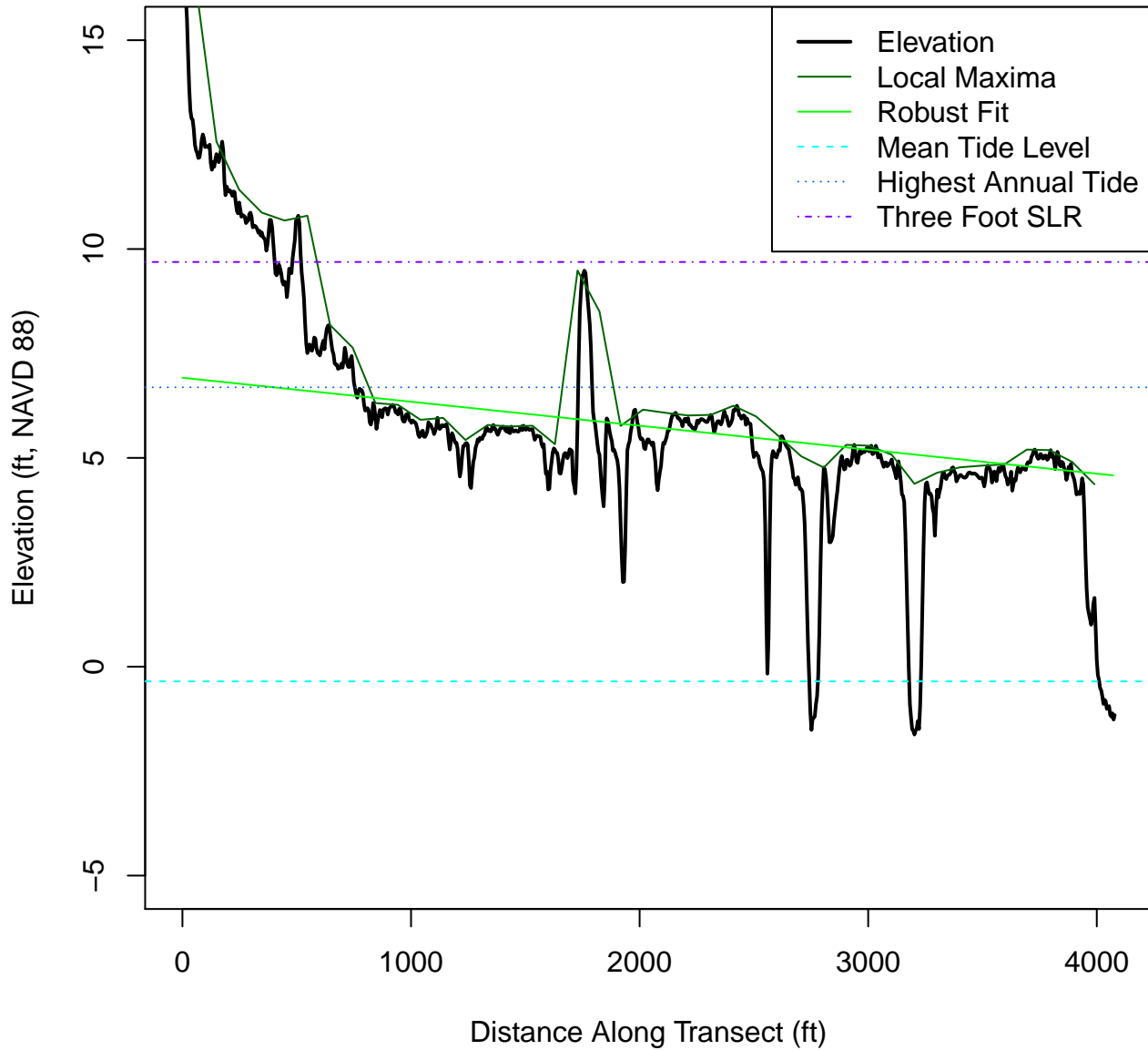
**Longitudinal Profile
TR42
Window = 11**



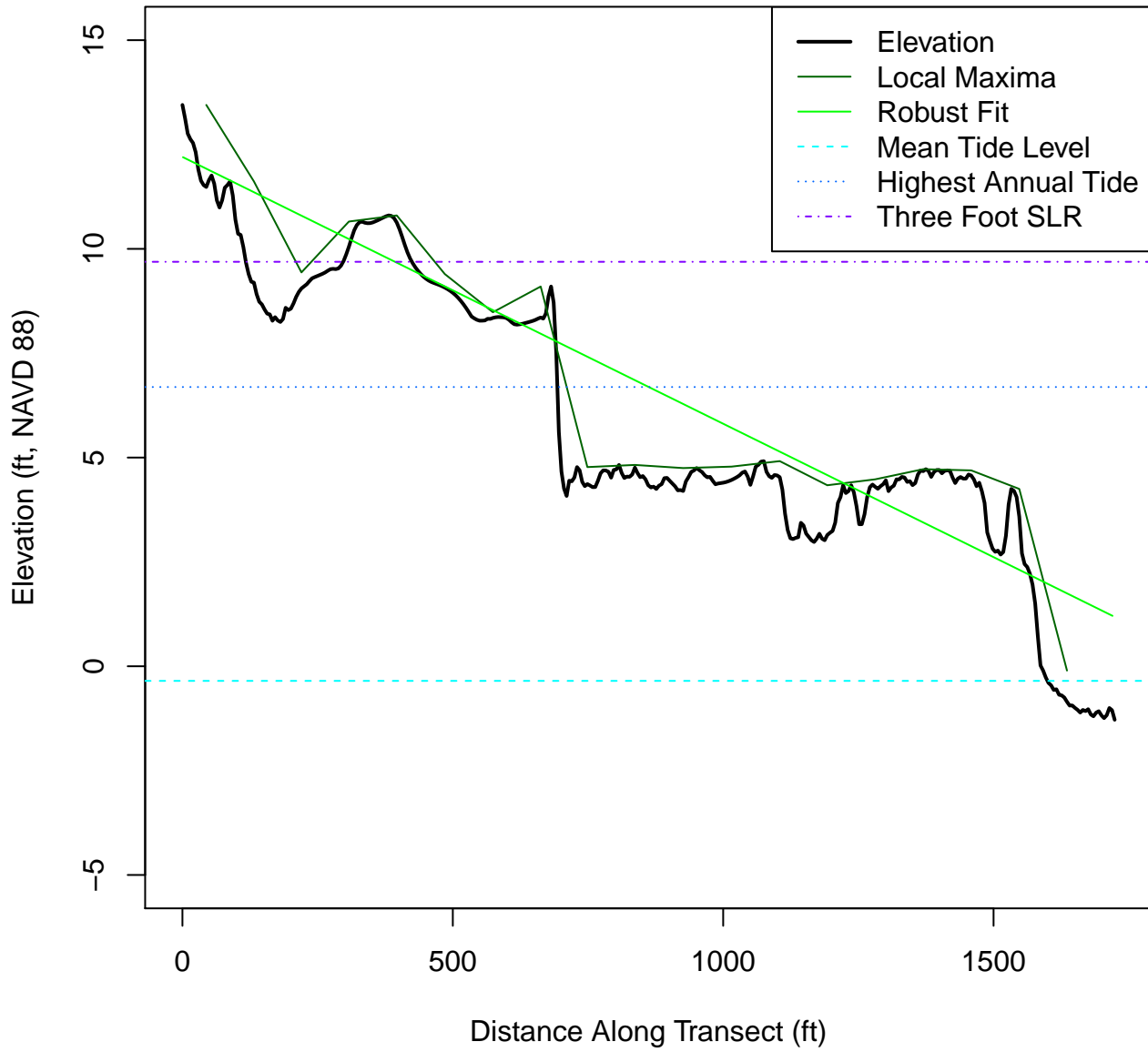
**Longitudinal Profile
TR43
Window = 15**



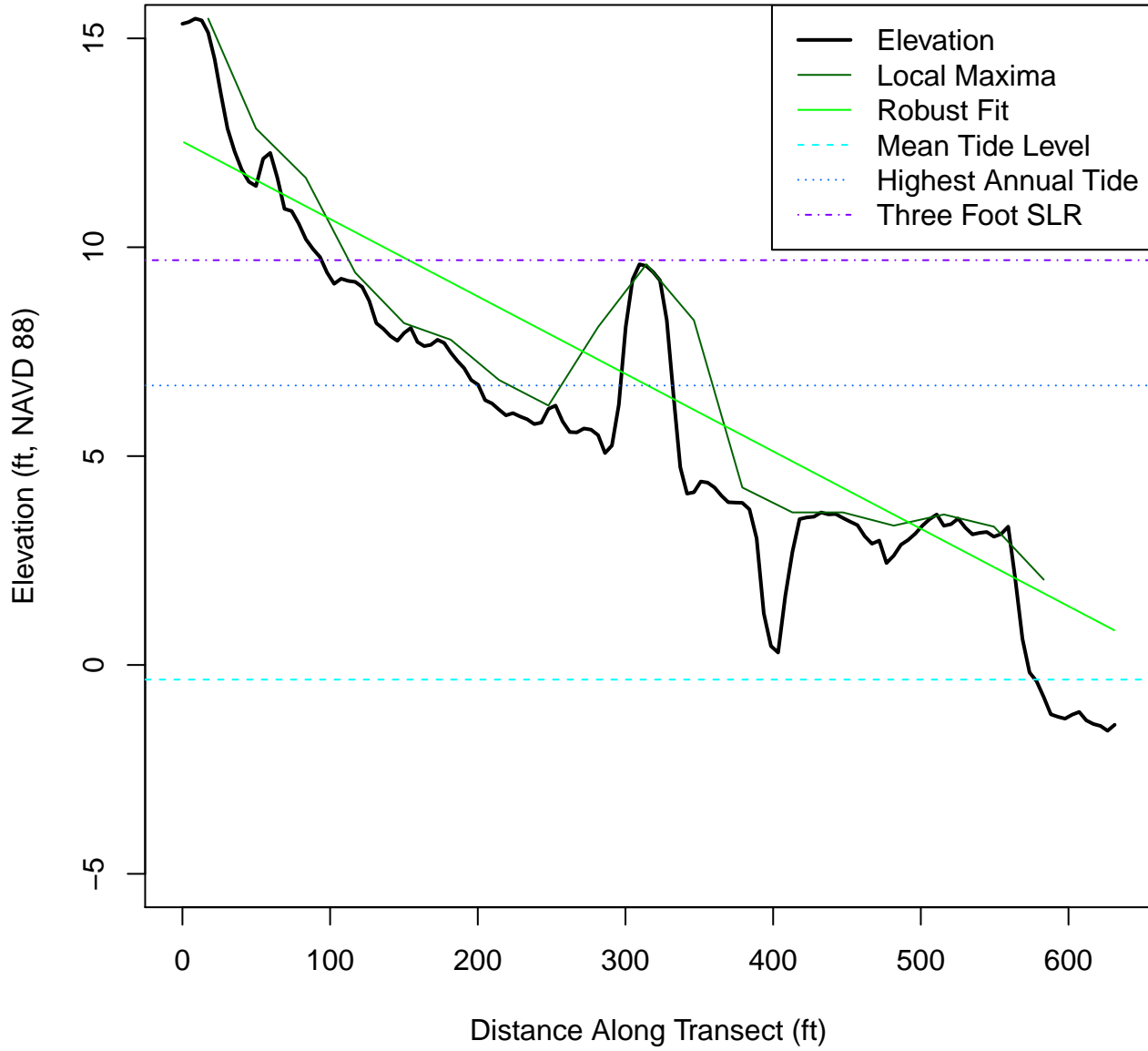
**Longitudinal Profile
TR44
Window = 20**



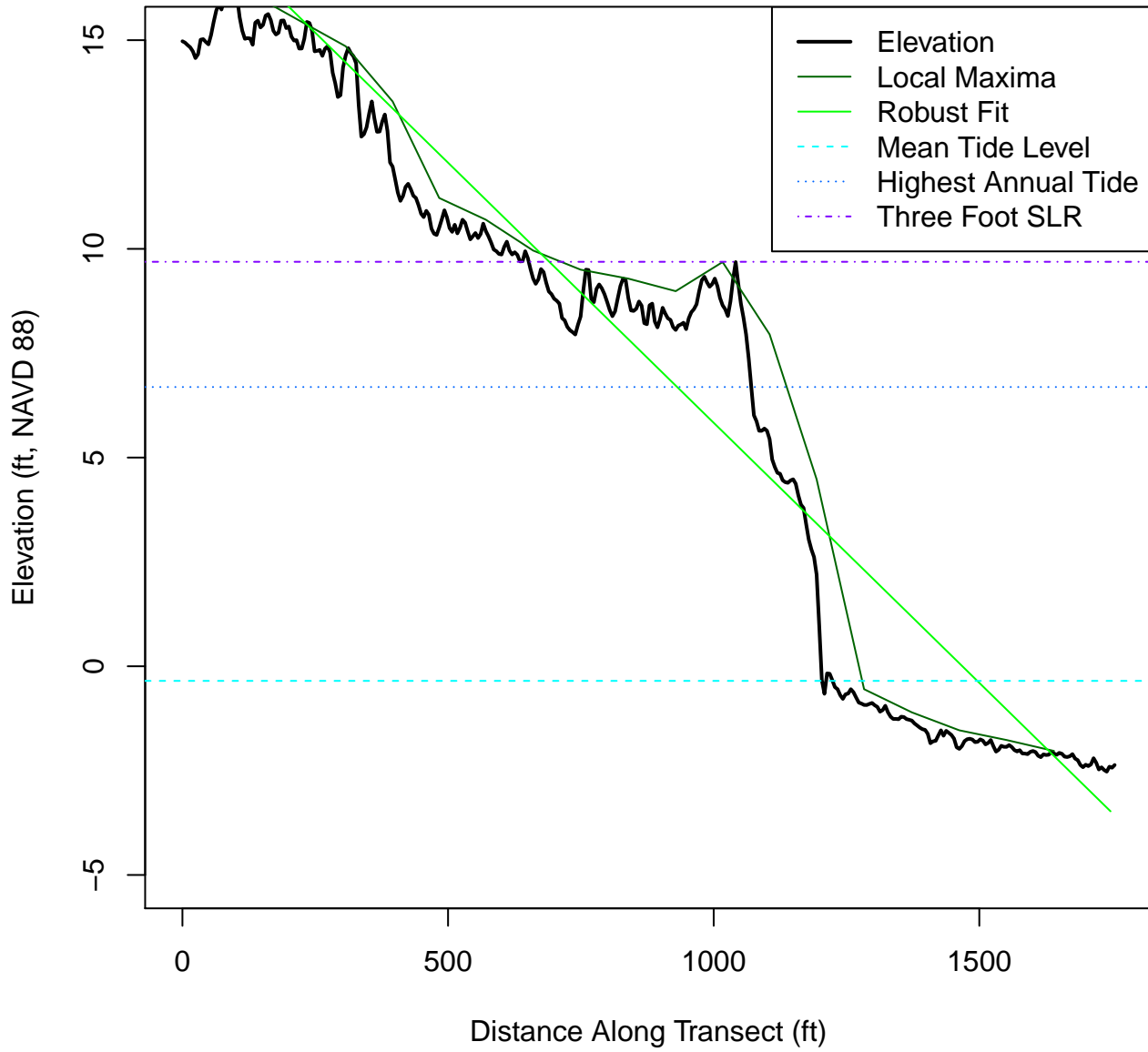
**Longitudinal Profile
TR45
Window = 18**



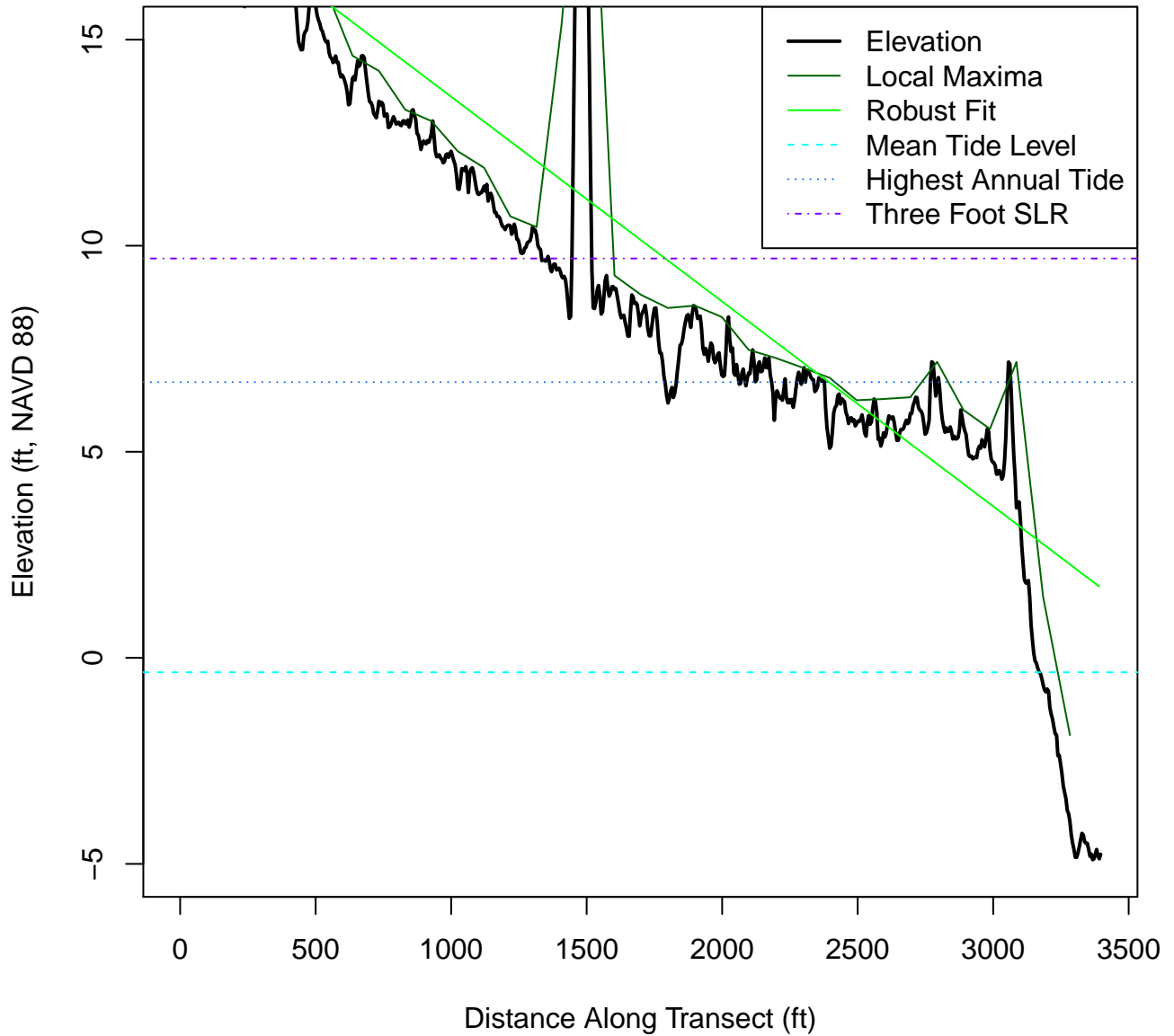
**Longitudinal Profile
TR46
Window = 7**



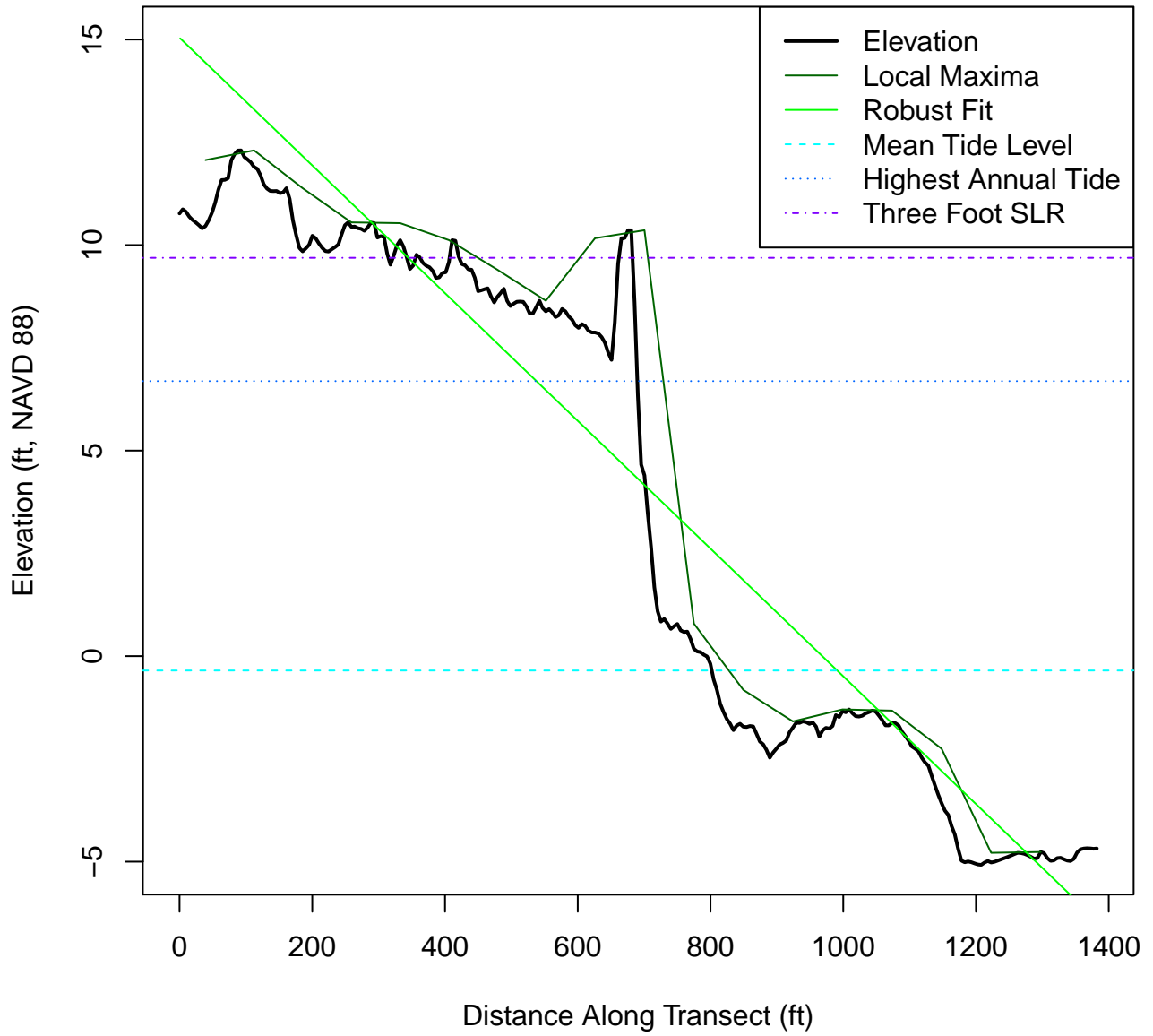
**Longitudinal Profile
TR47
Window = 18**



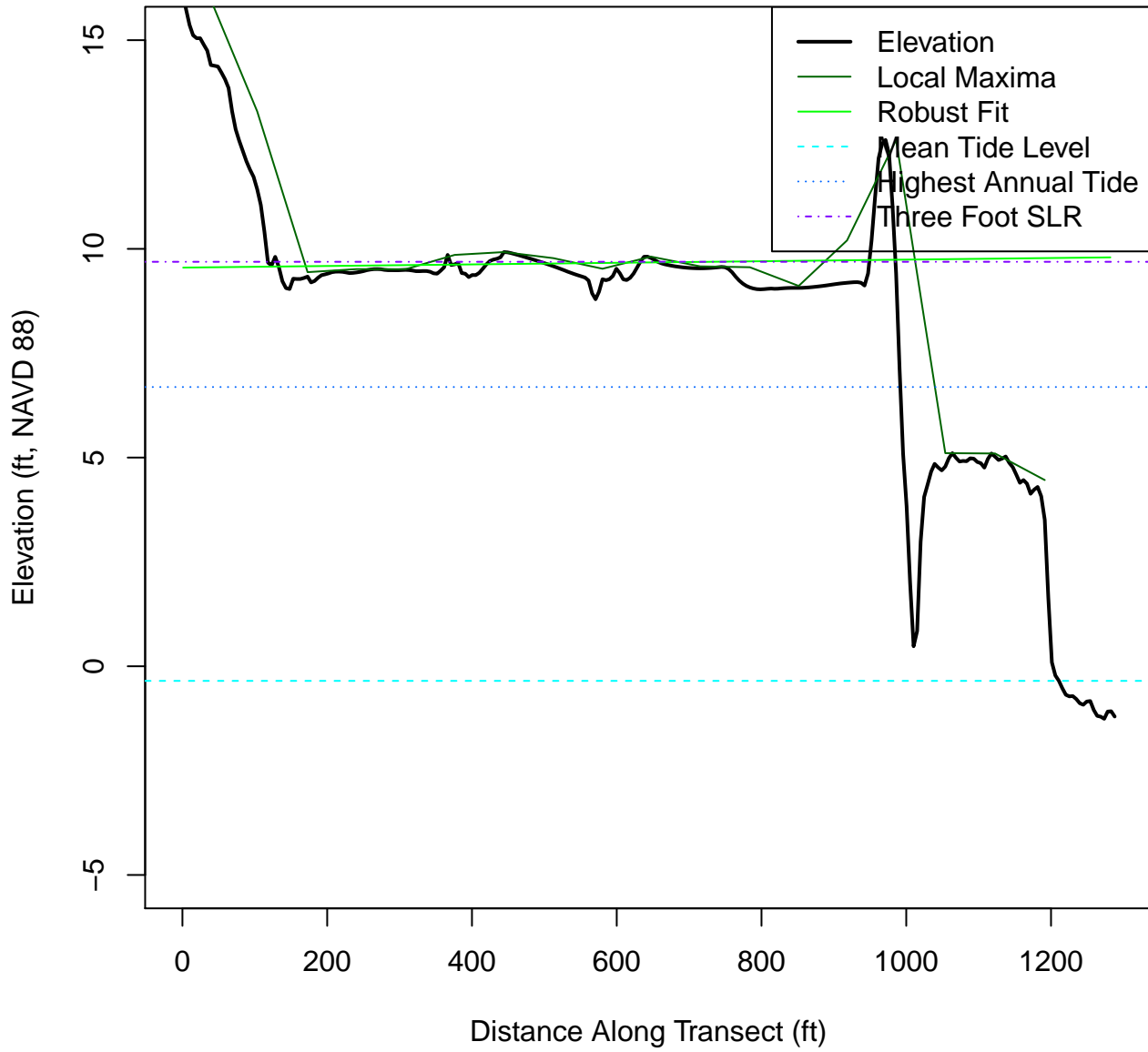
**Longitudinal Profile
TR48
Window = 20**



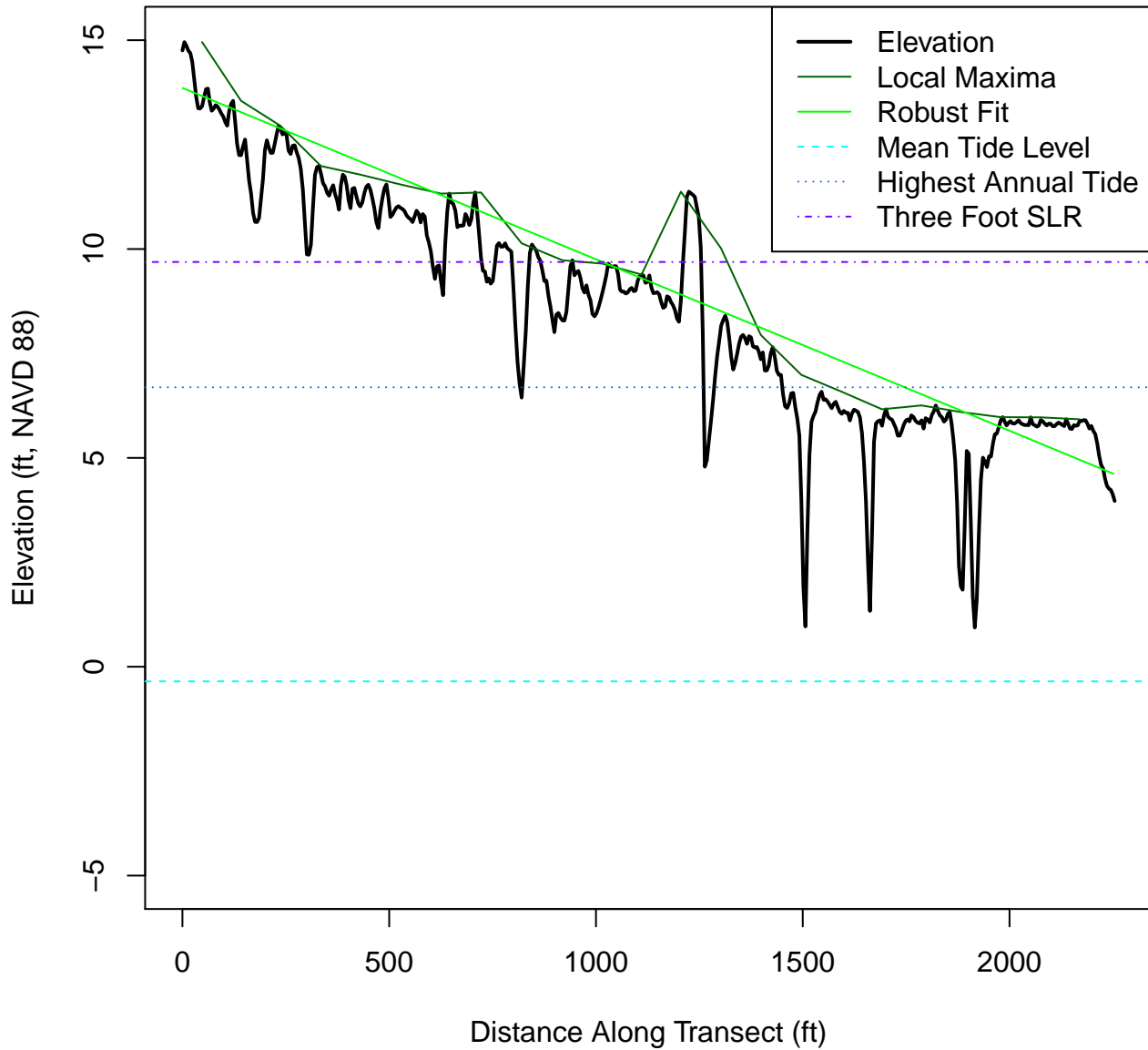
**Longitudinal Profile
TR49
Window = 15**



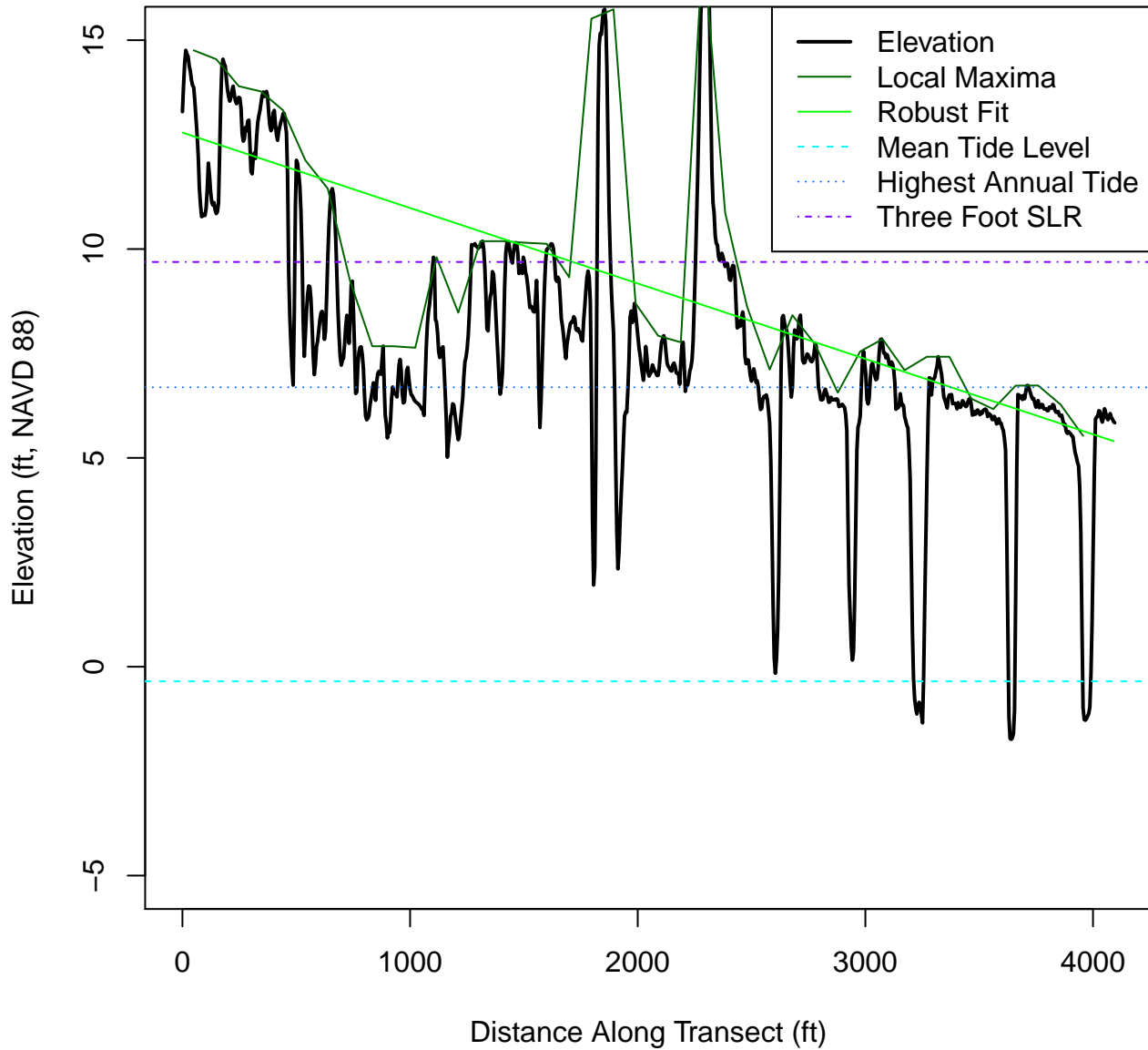
**Longitudinal Profile
TR50
Window = 14**



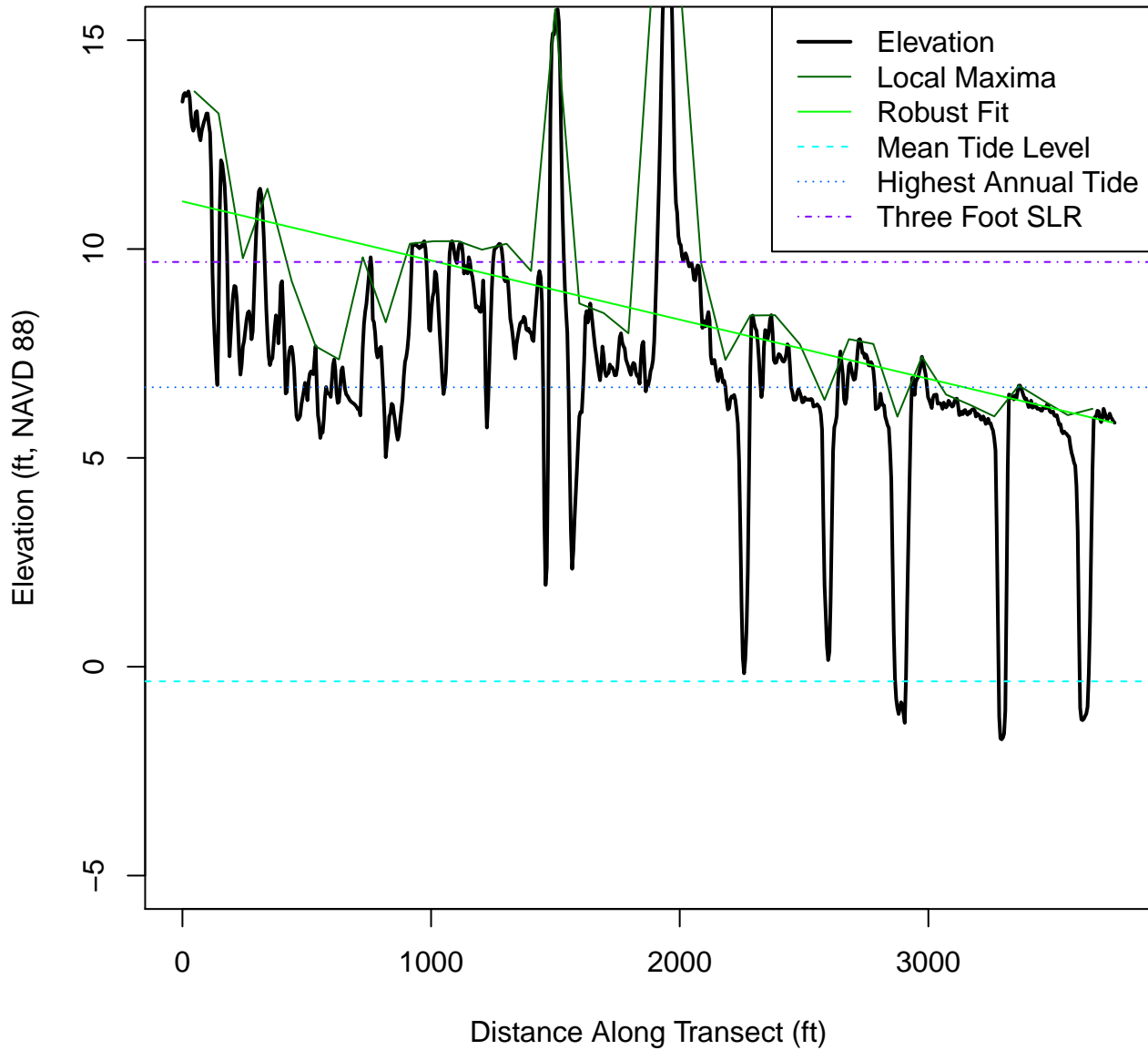
**Longitudinal Profile
TR51
Window = 20**



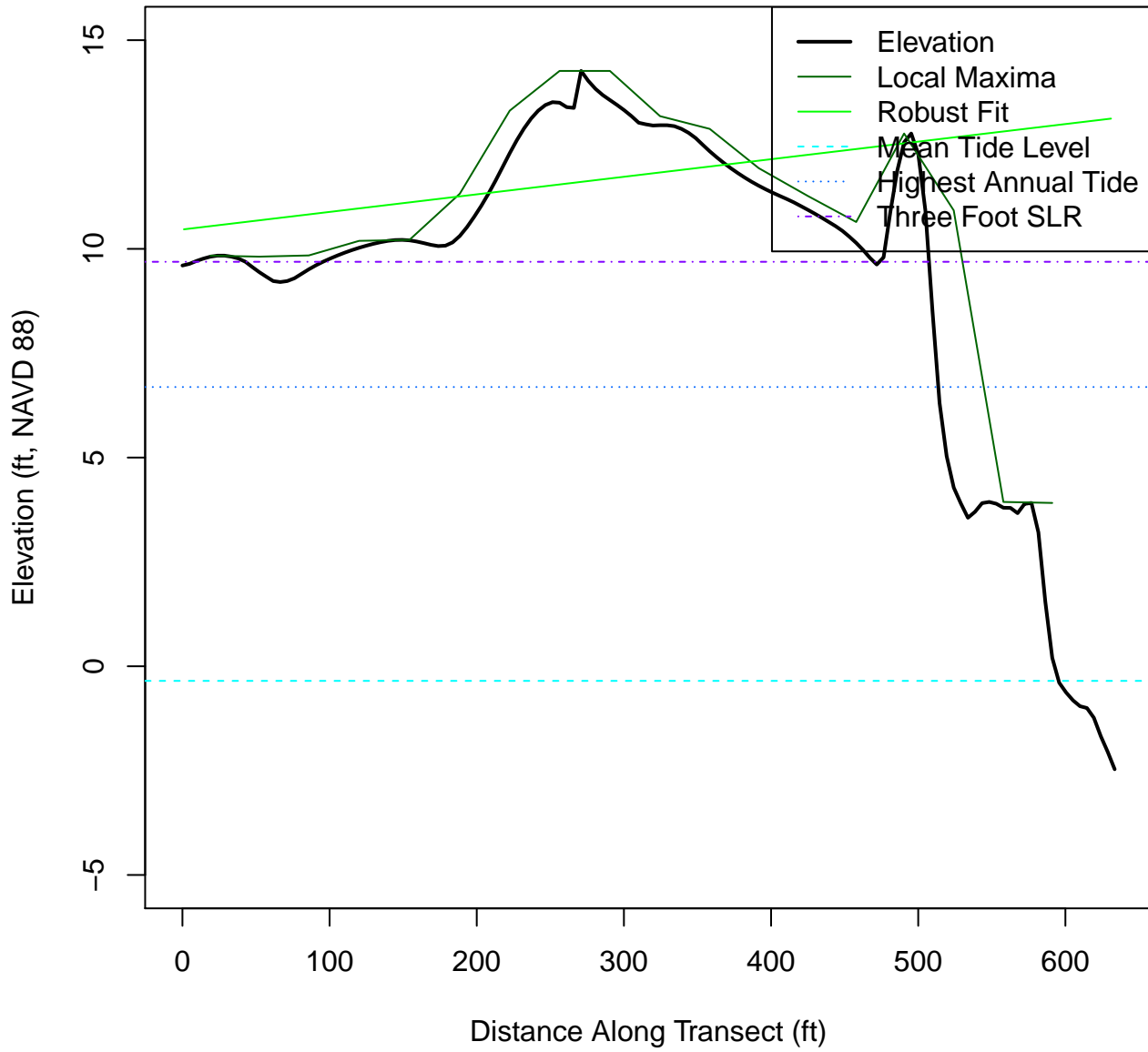
**Longitudinal Profile
TR52
Window = 20**



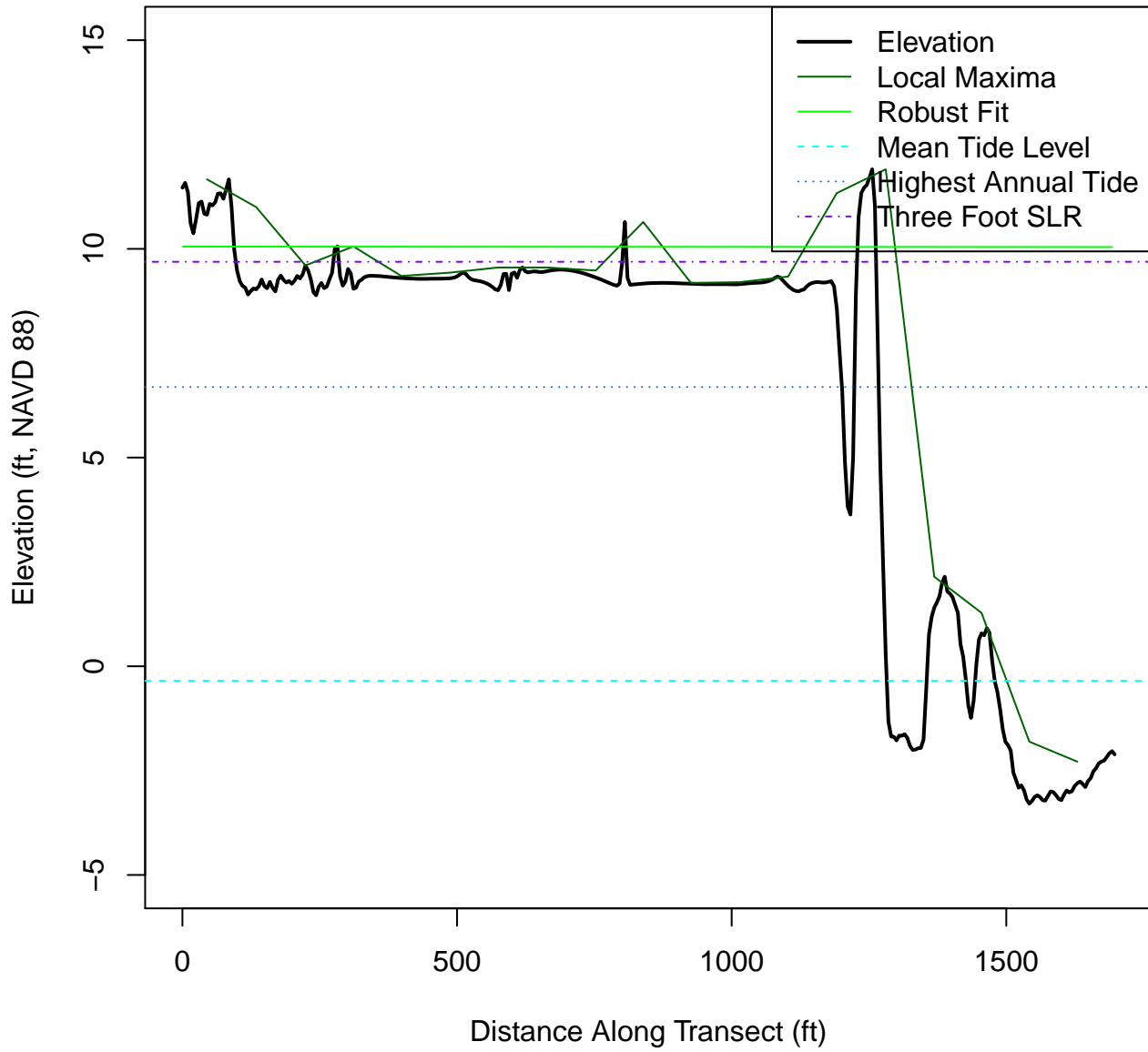
**Longitudinal Profile
TR53
Window = 20**



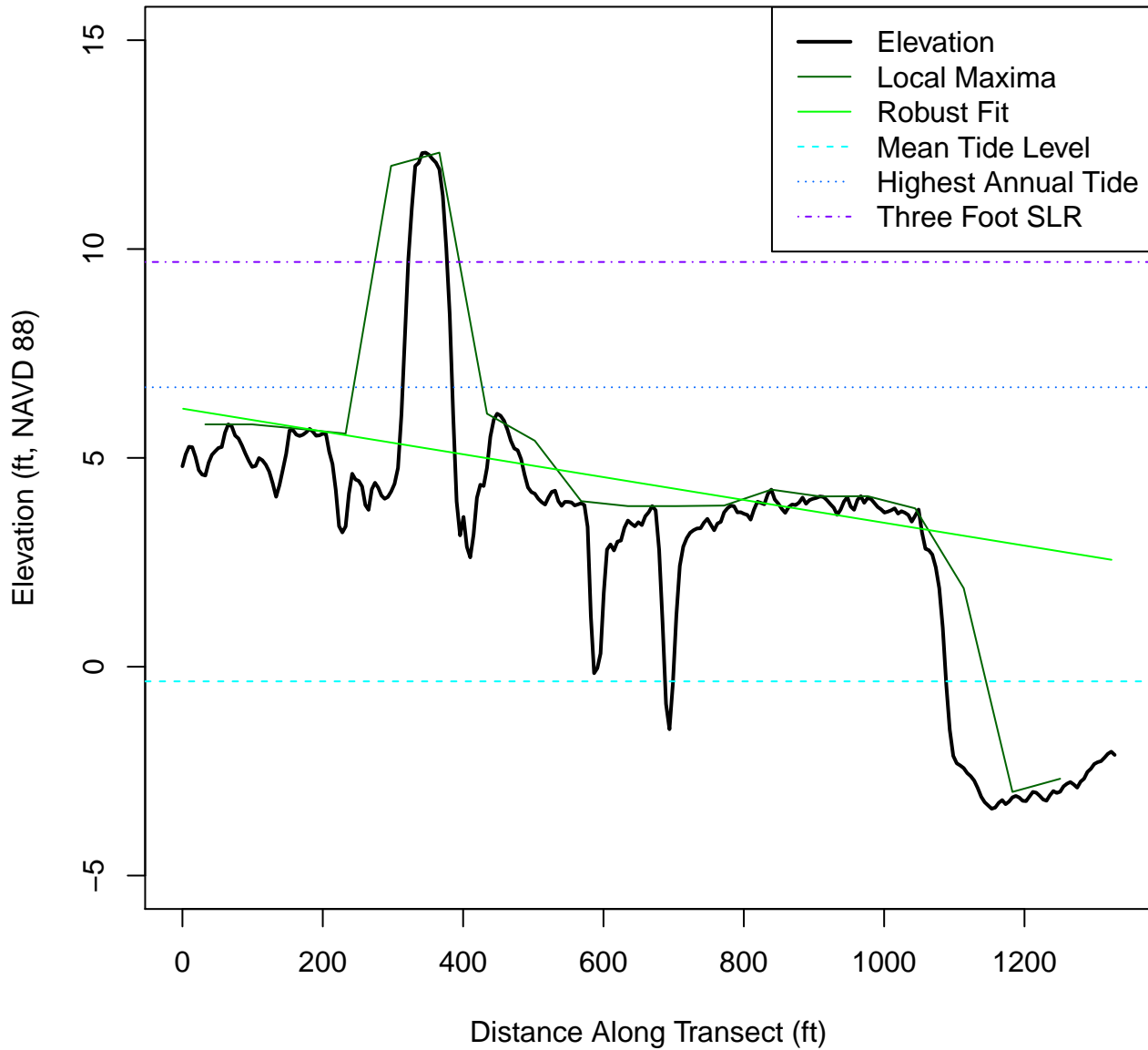
**Longitudinal Profile
TR54
Window = 7**



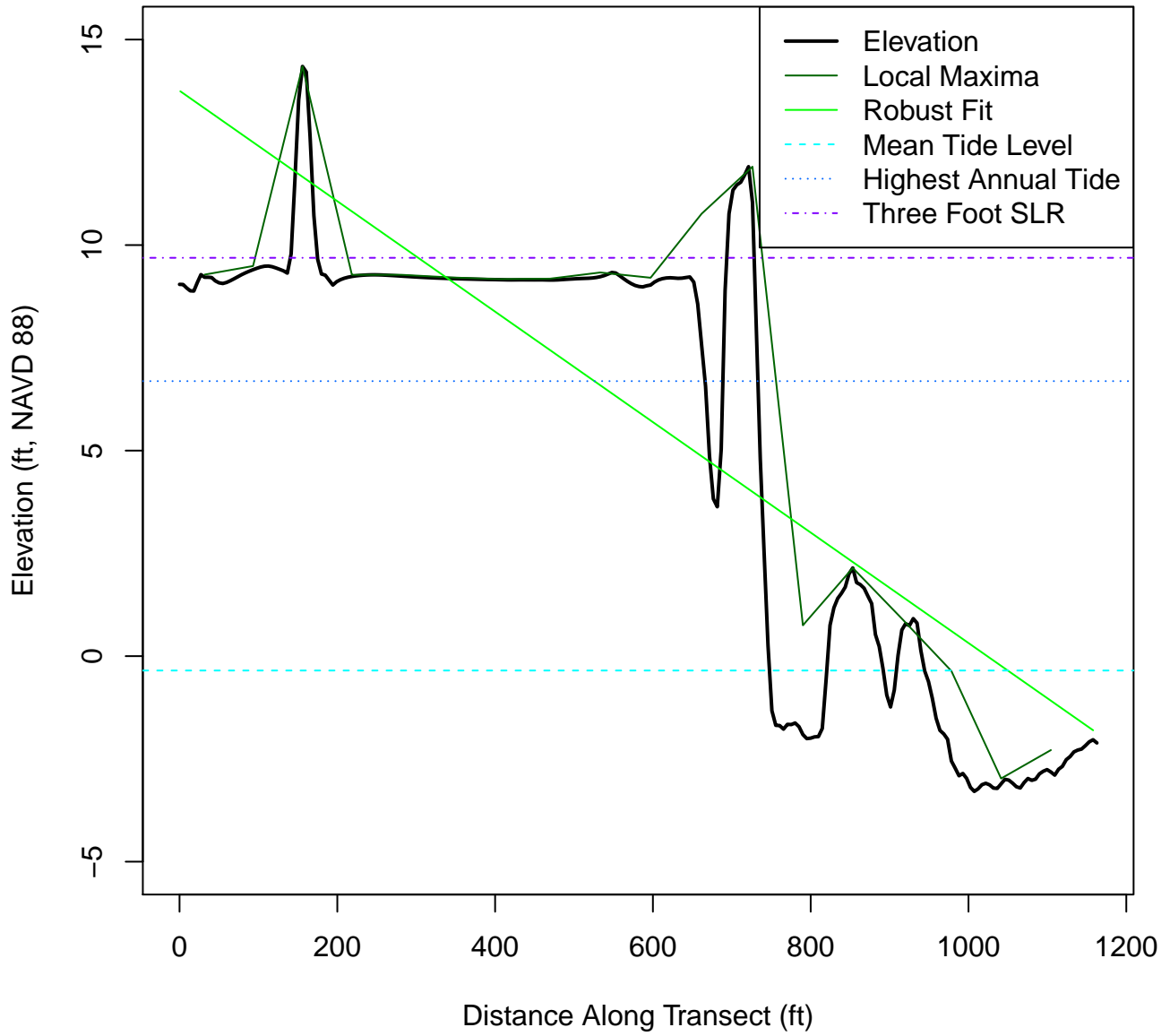
**Longitudinal Profile
TR55
Window = 18**



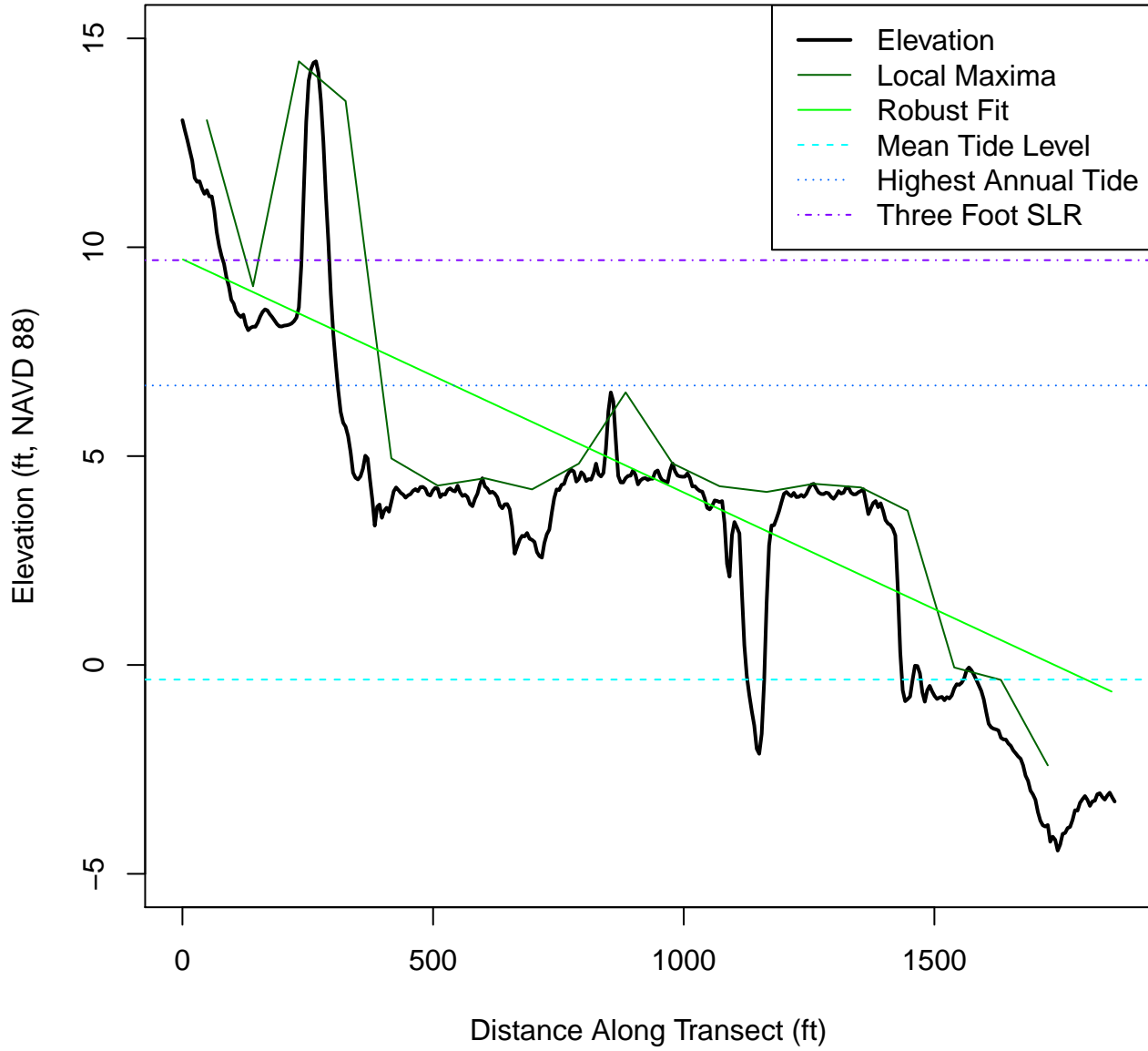
**Longitudinal Profile
TR56
Window = 14**



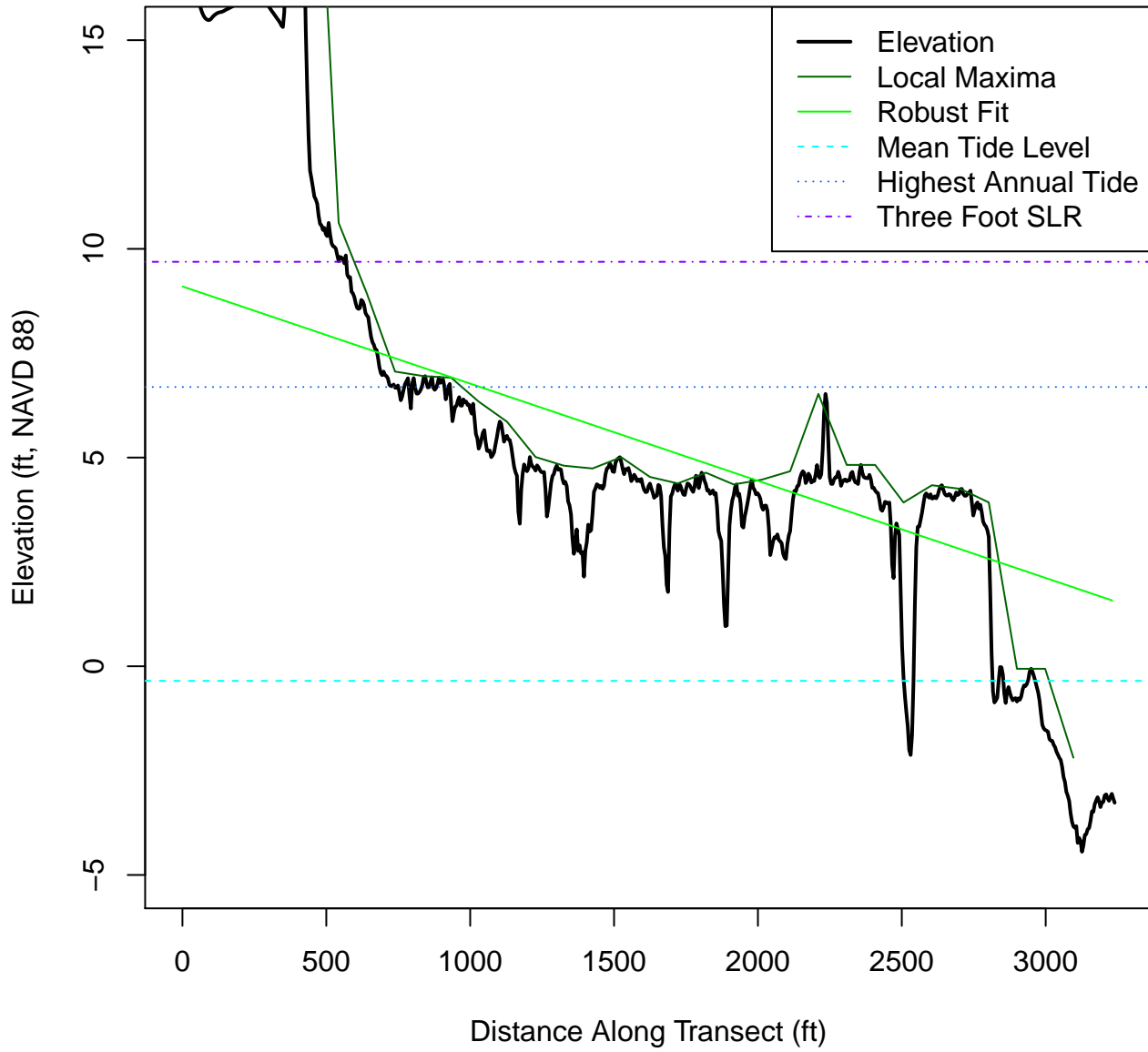
**Longitudinal Profile
TR57
Window = 13**



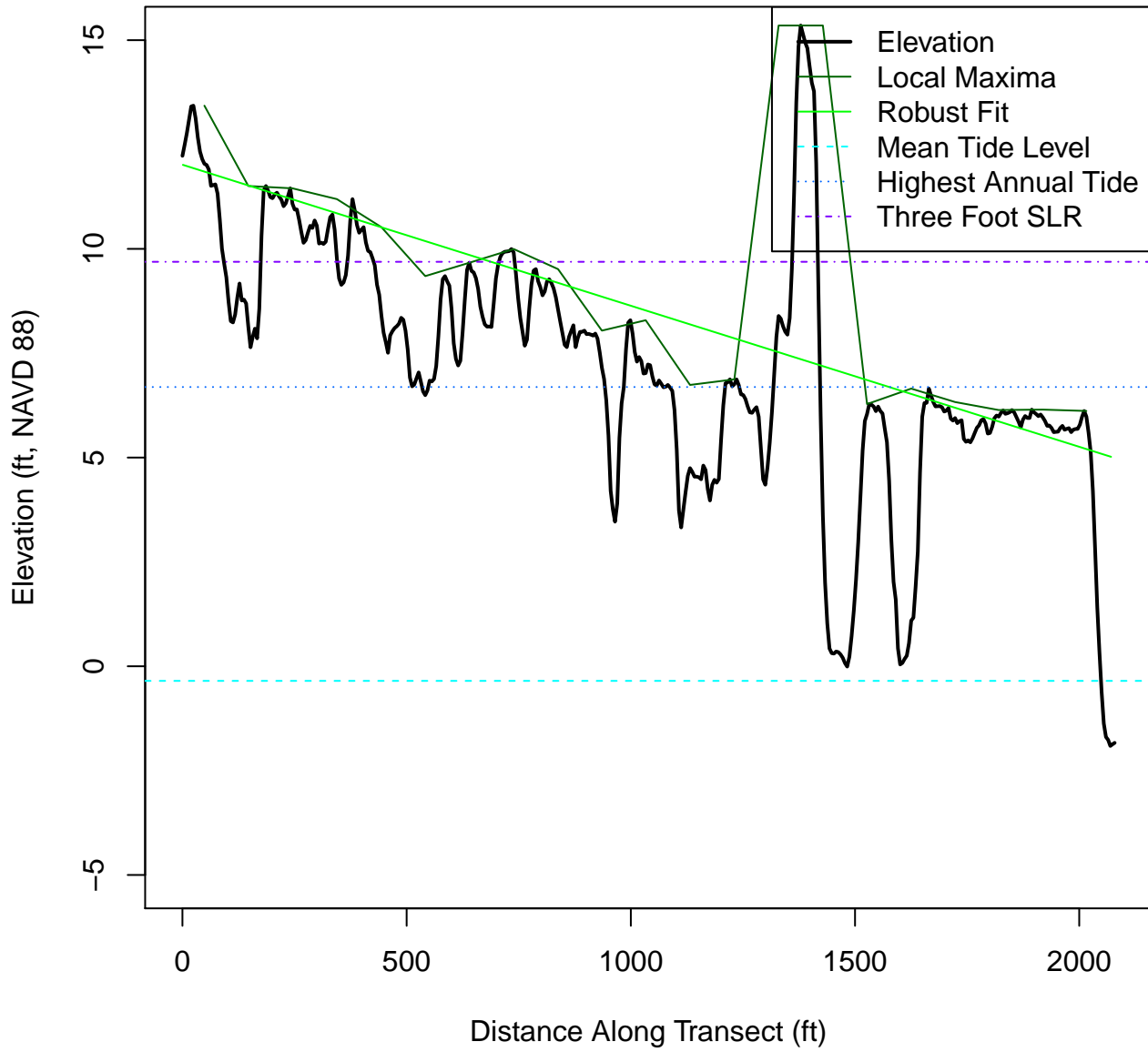
**Longitudinal Profile
TR58
Window = 19**



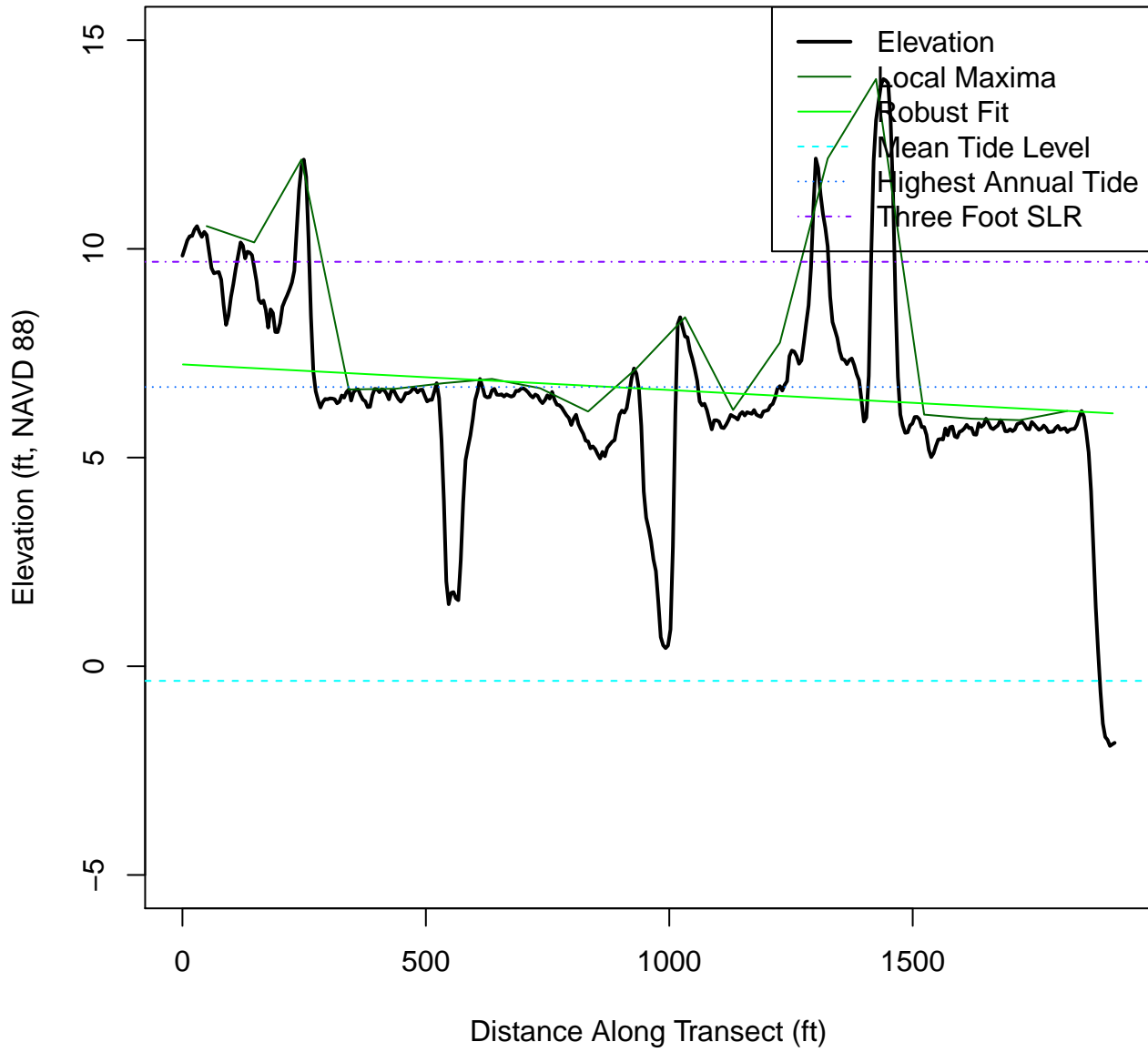
**Longitudinal Profile
TR59
Window = 20**



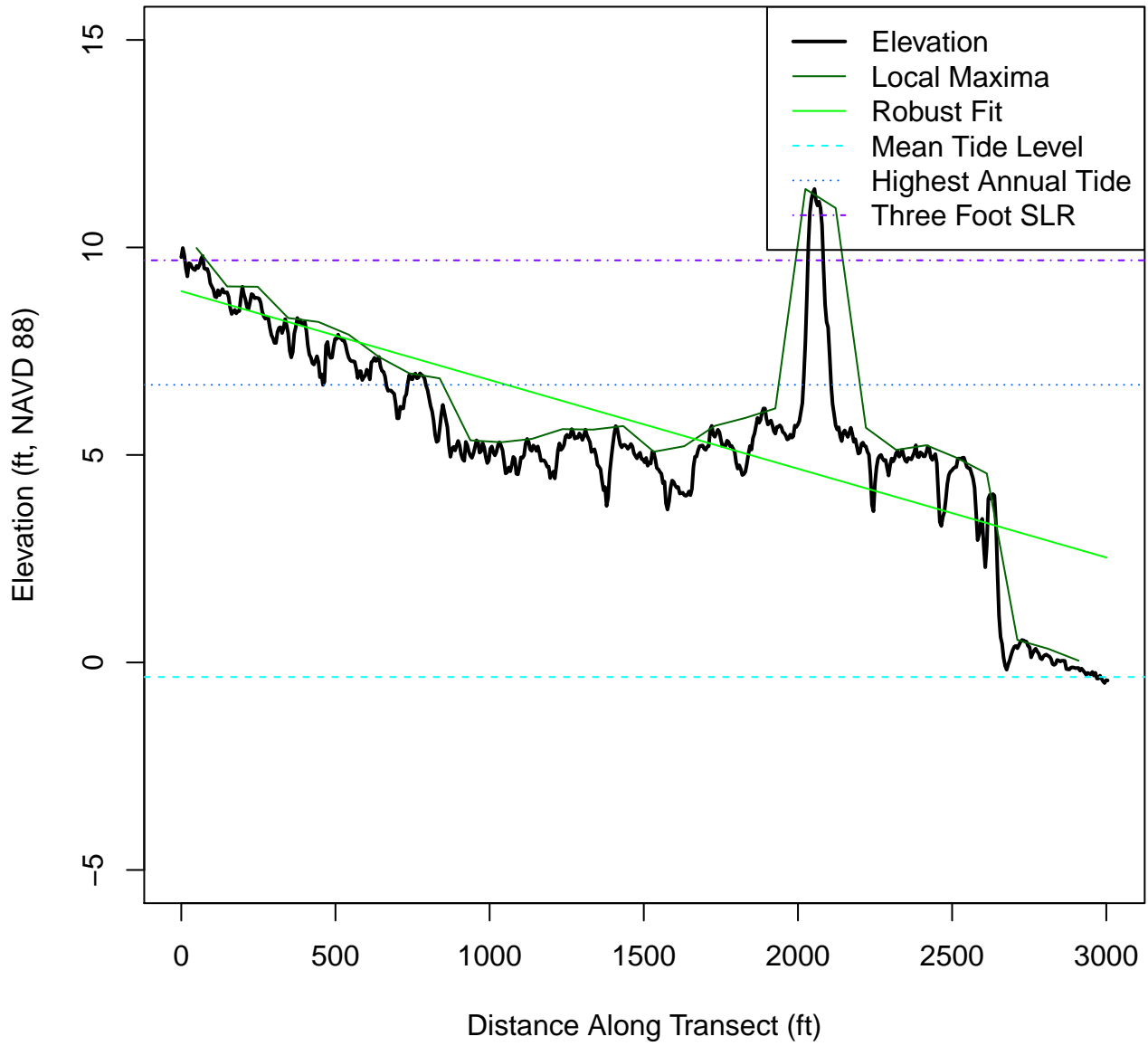
**Longitudinal Profile
TR60
Window = 20**



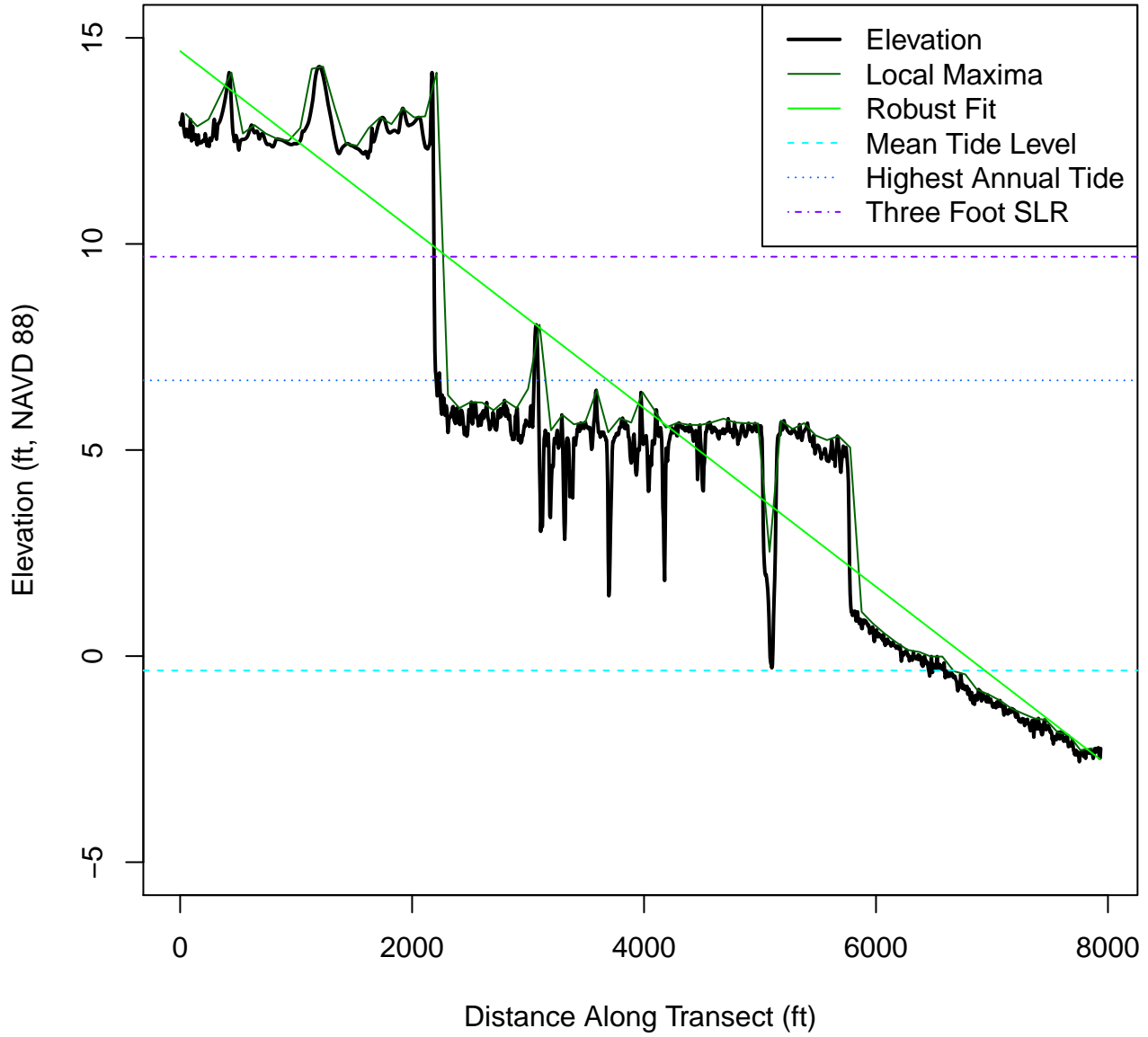
**Longitudinal Profile
TR61
Window = 20**



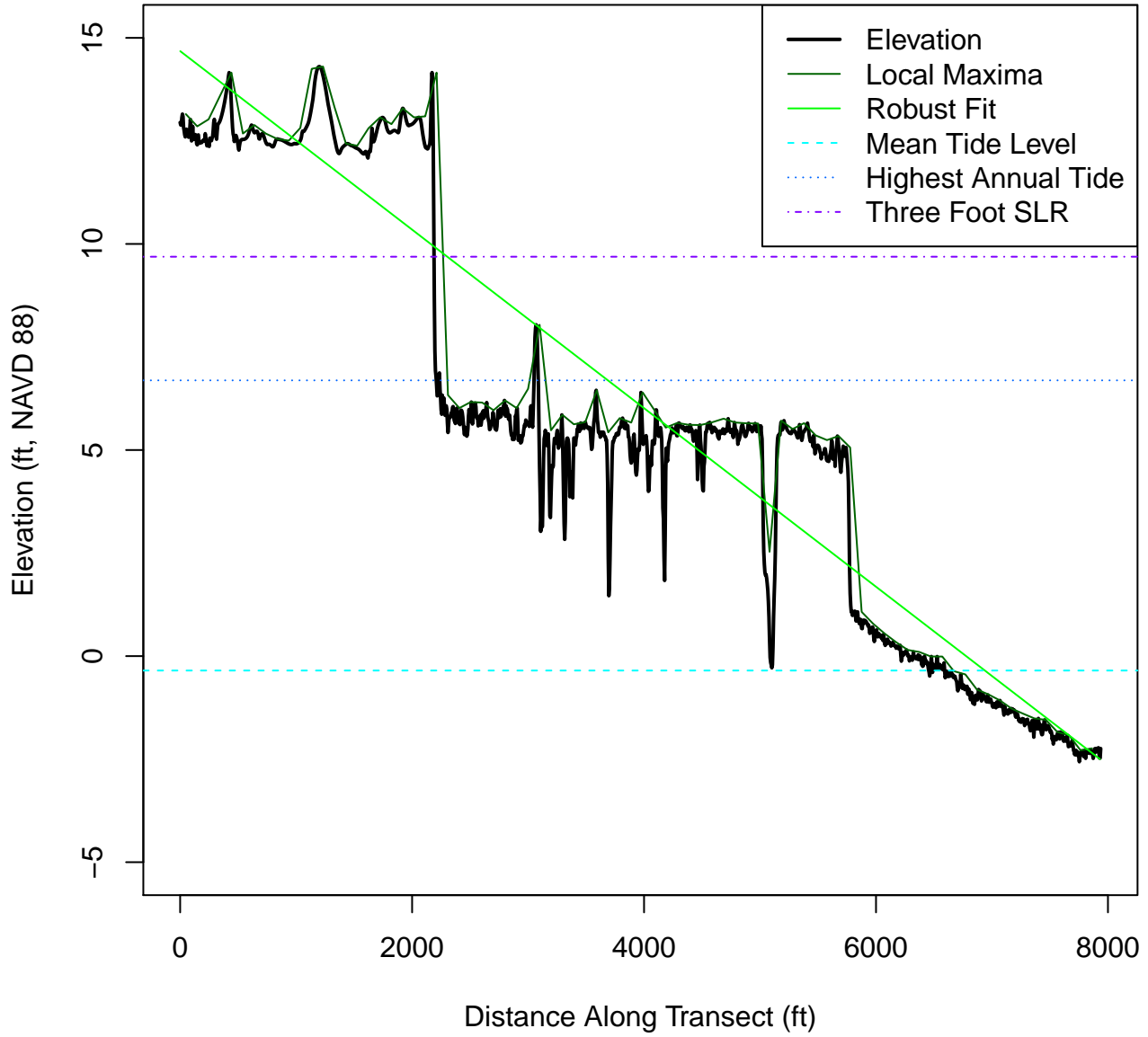
**Longitudinal Profile
TR62
Window = 20**



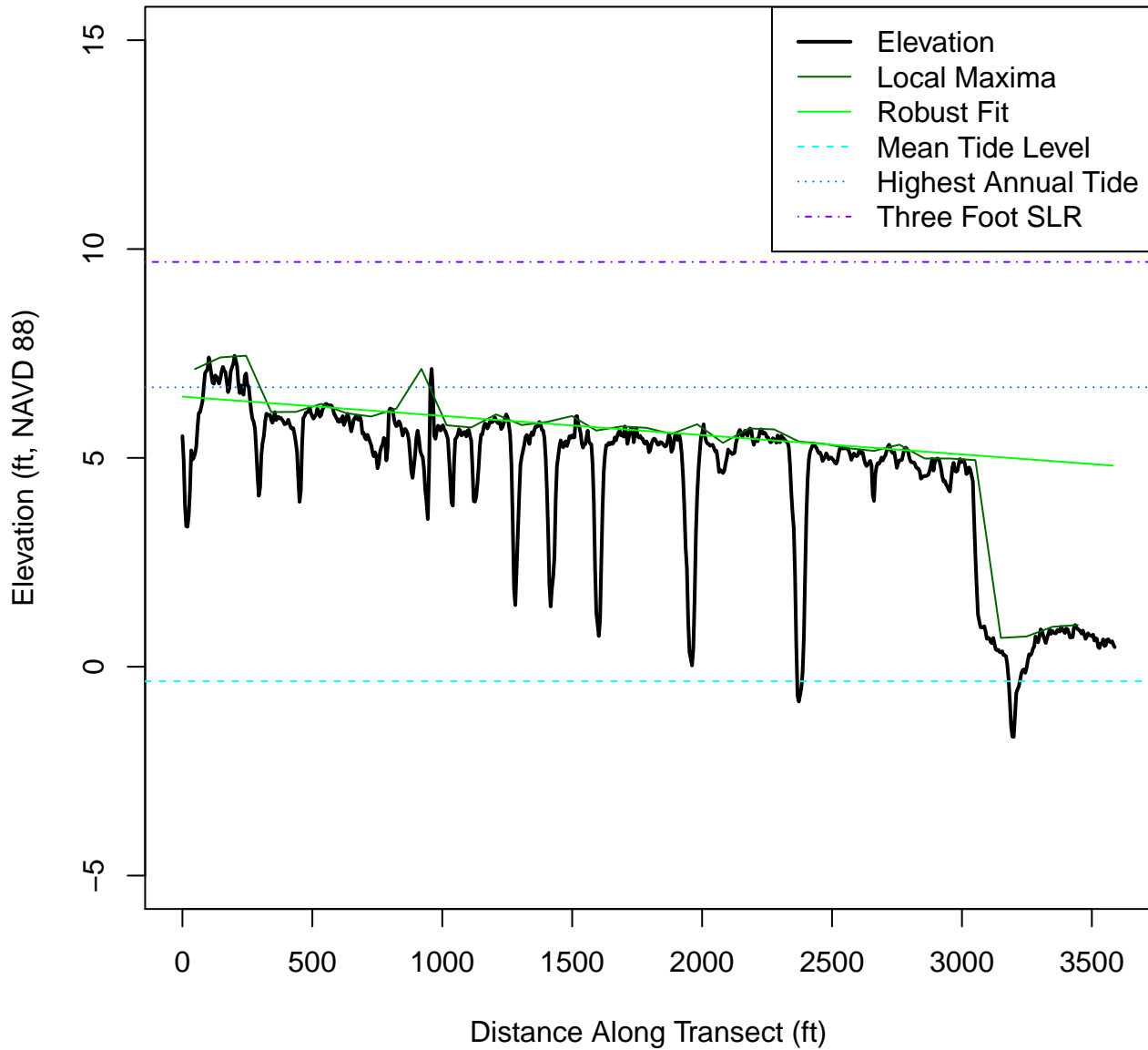
**Longitudinal Profile
TR63
Window = 20**



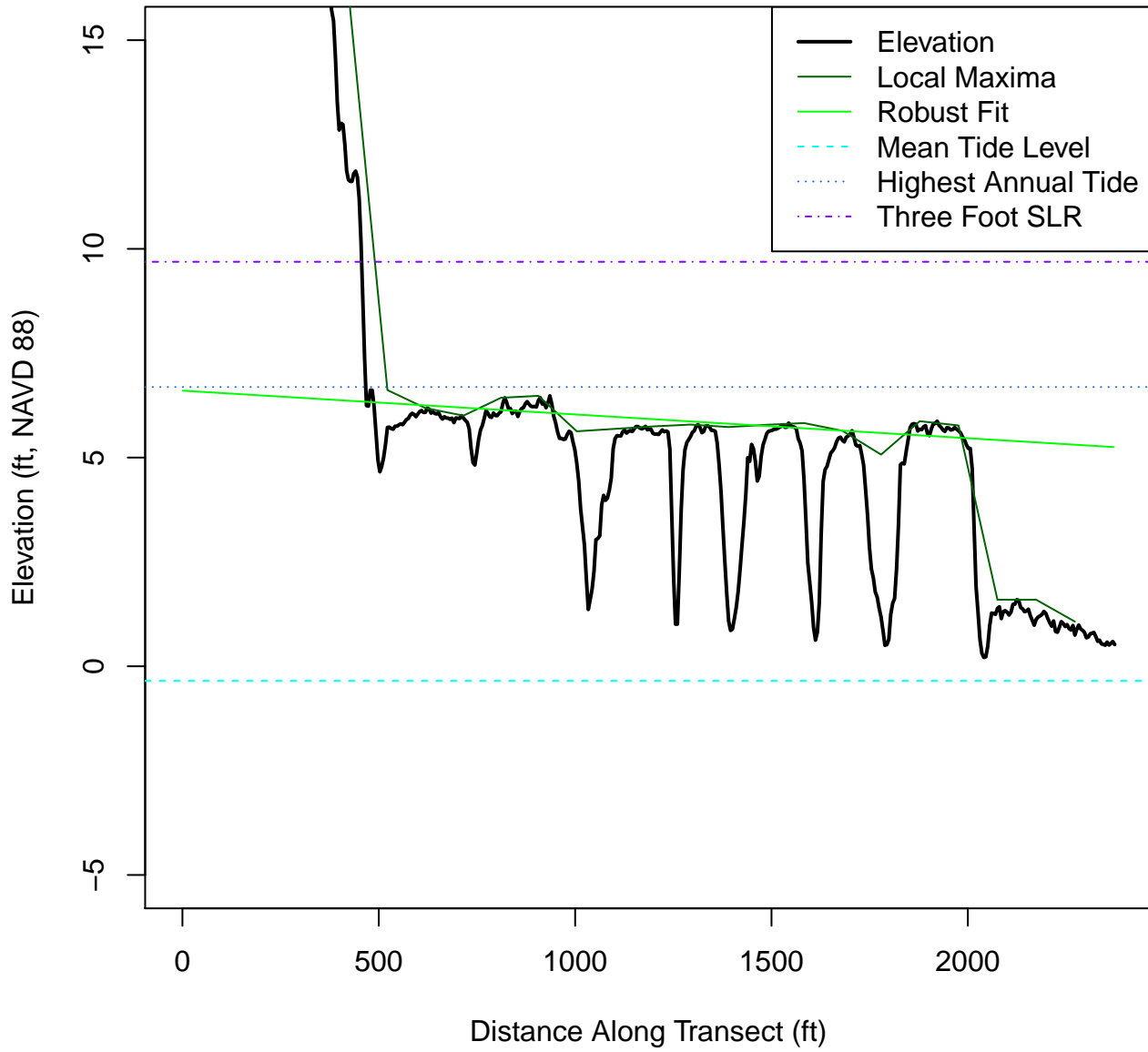
**Longitudinal Profile
TR64
Window = 20**



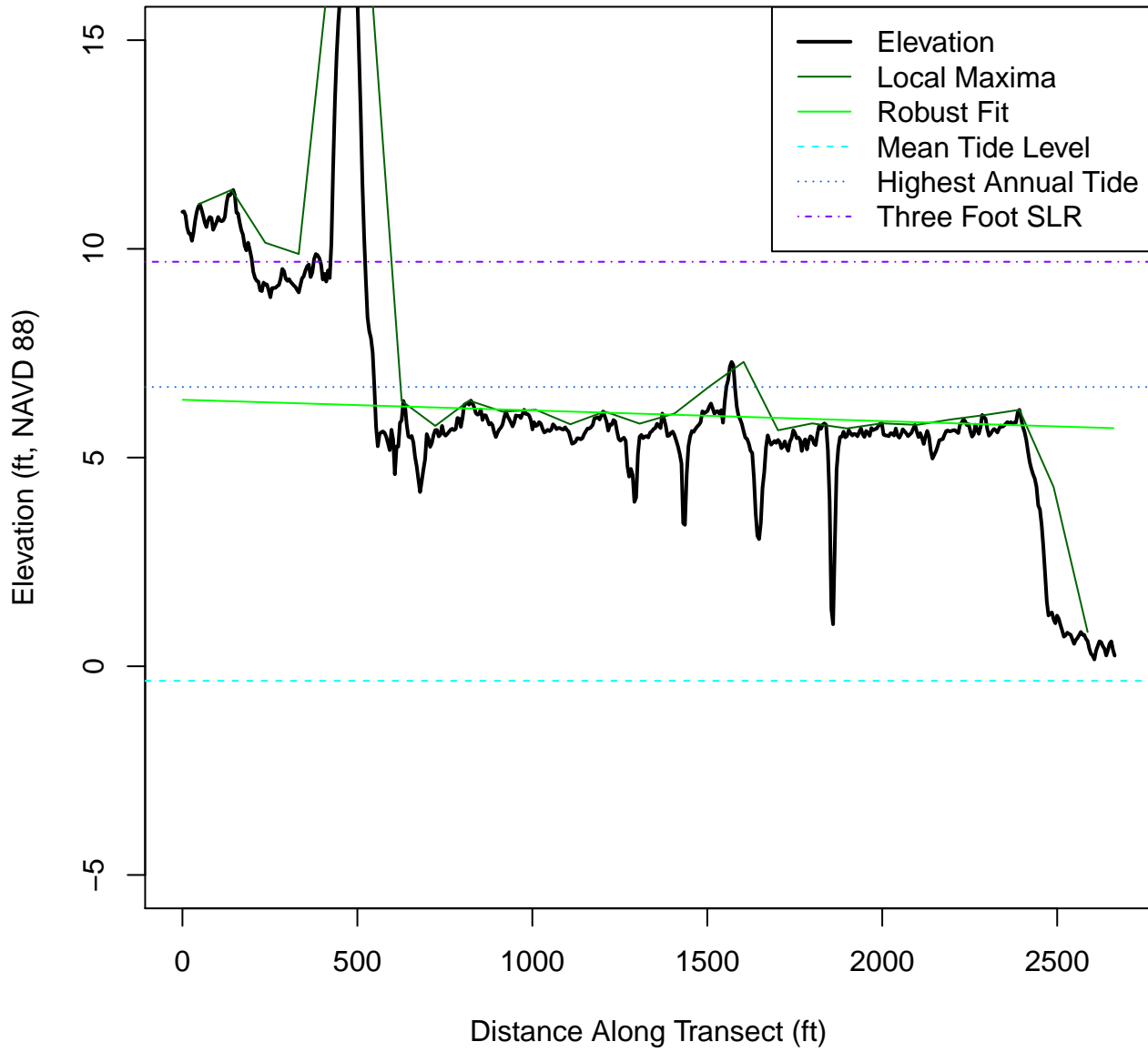
**Longitudinal Profile
TR65
Window = 20**



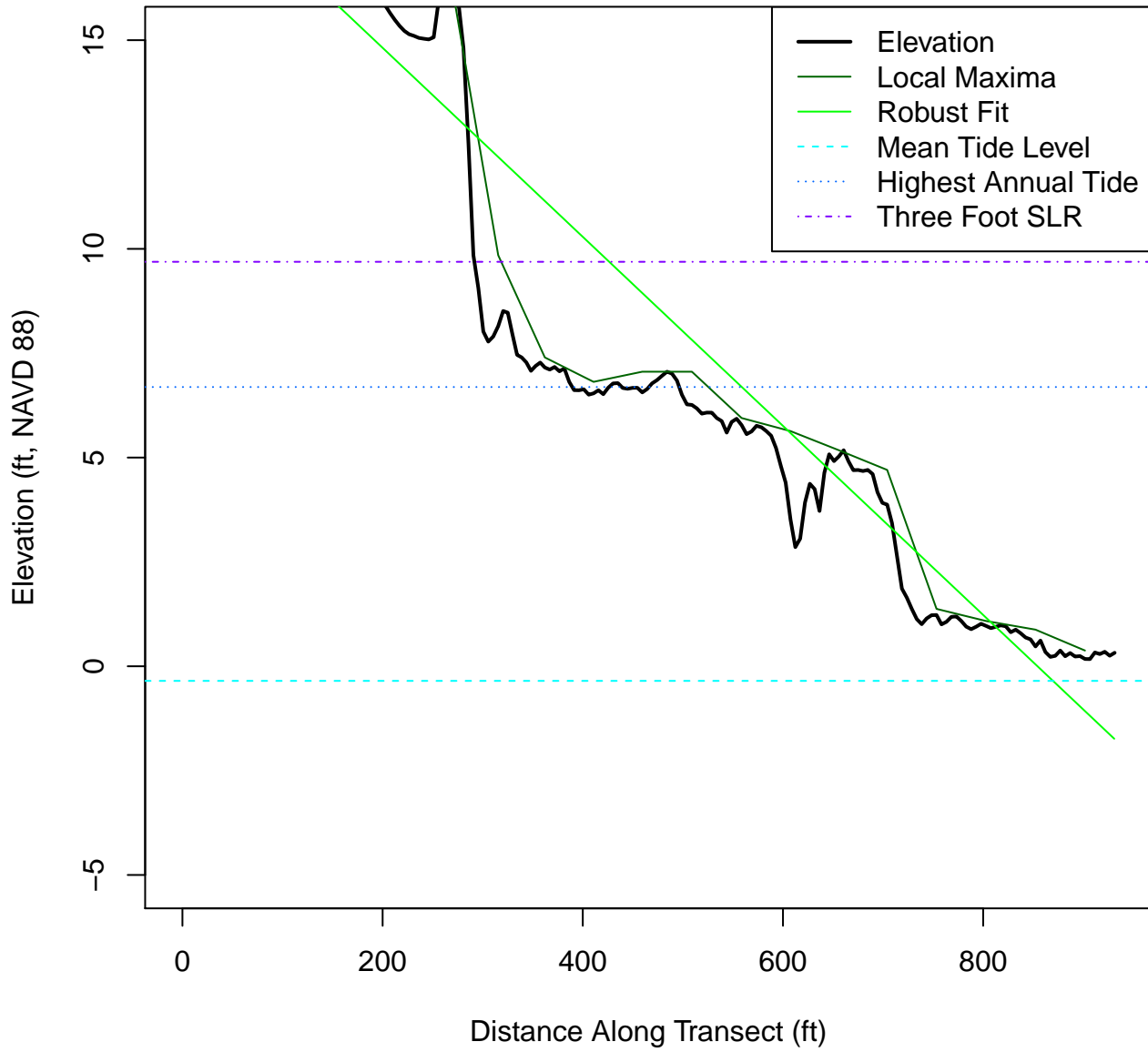
**Longitudinal Profile
TR66
Window = 20**



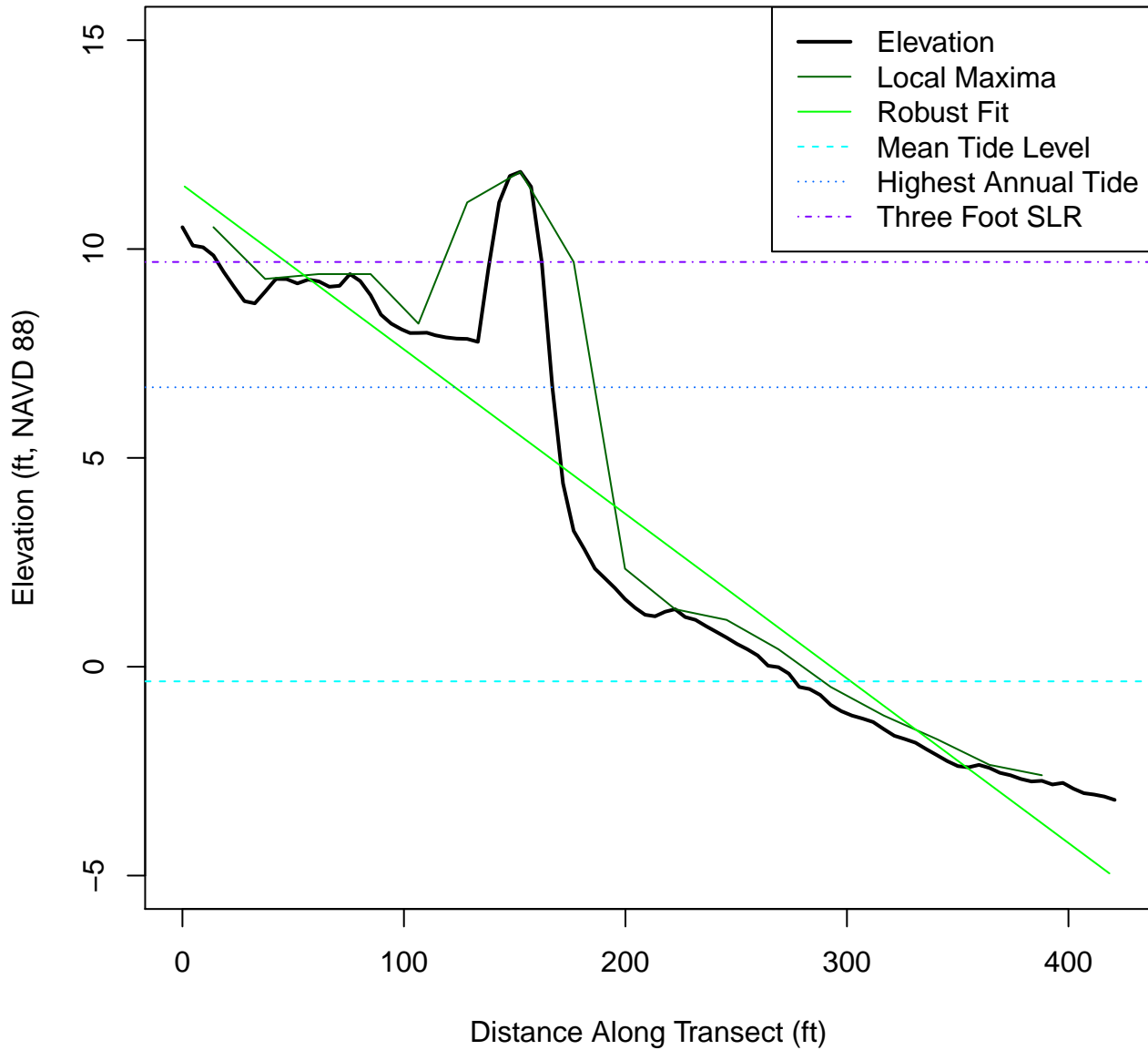
**Longitudinal Profile
TR67
Window = 20**



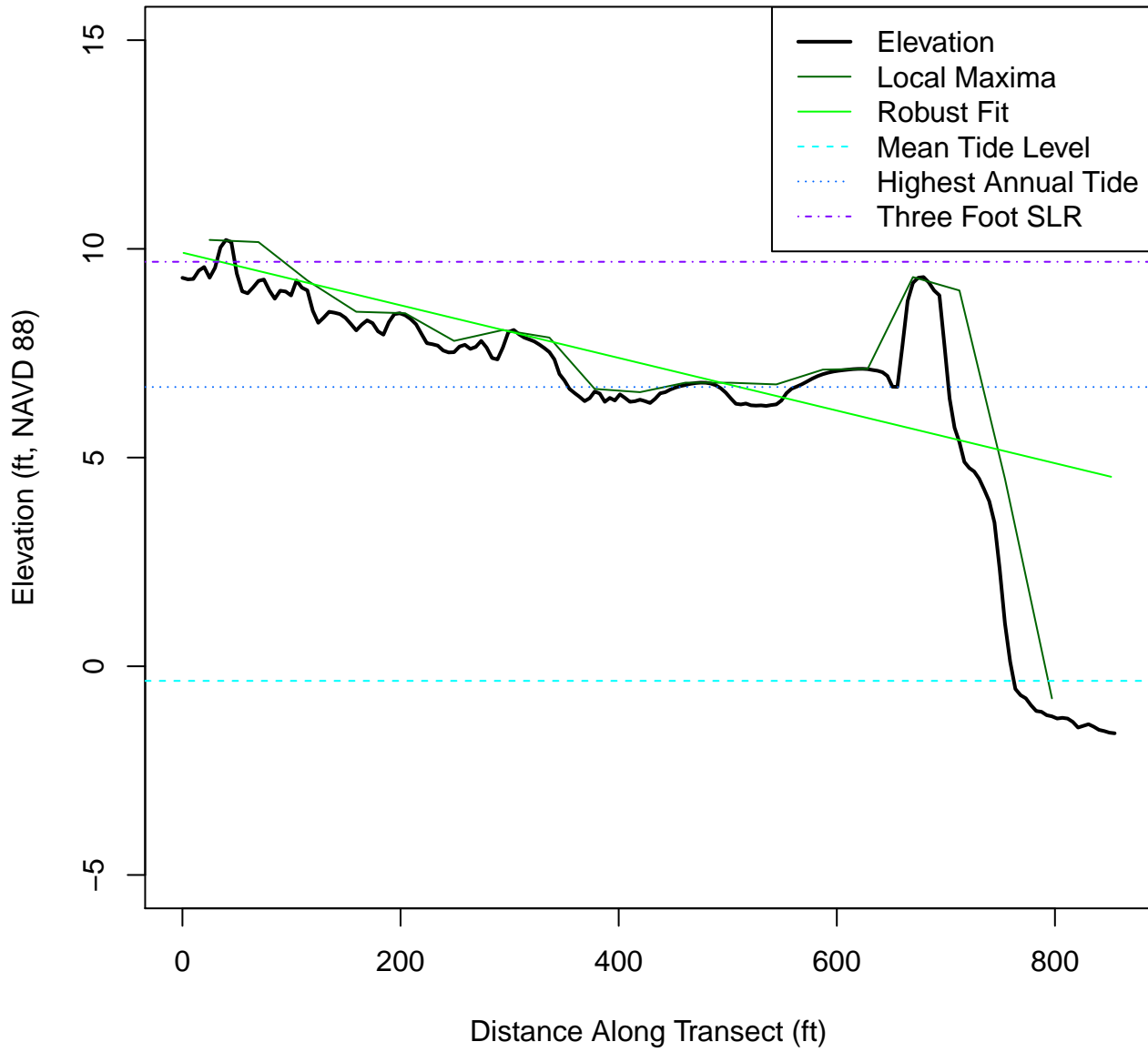
**Longitudinal Profile
TR68
Window = 10**



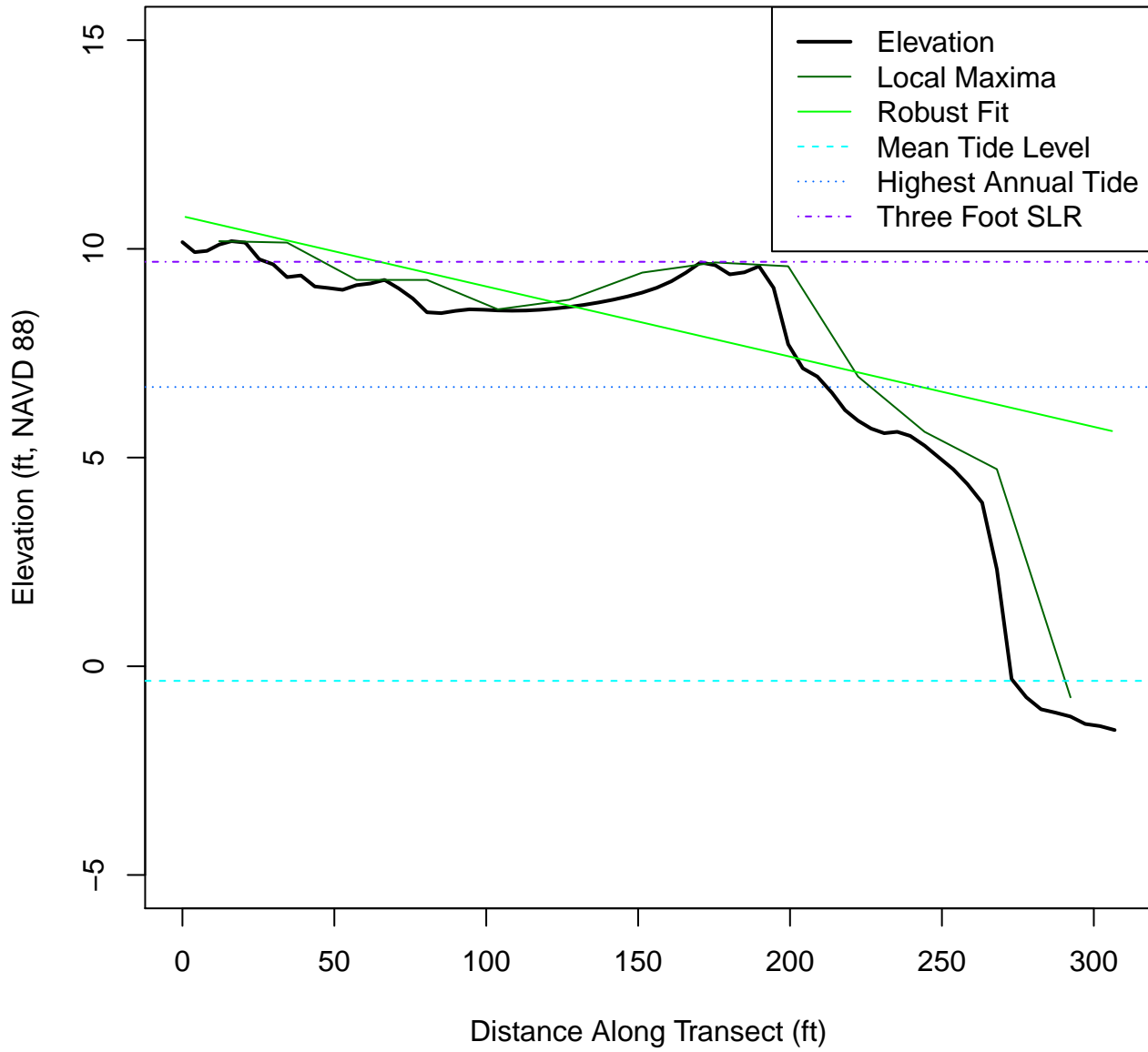
**Longitudinal Profile
TR69
Window = 5**



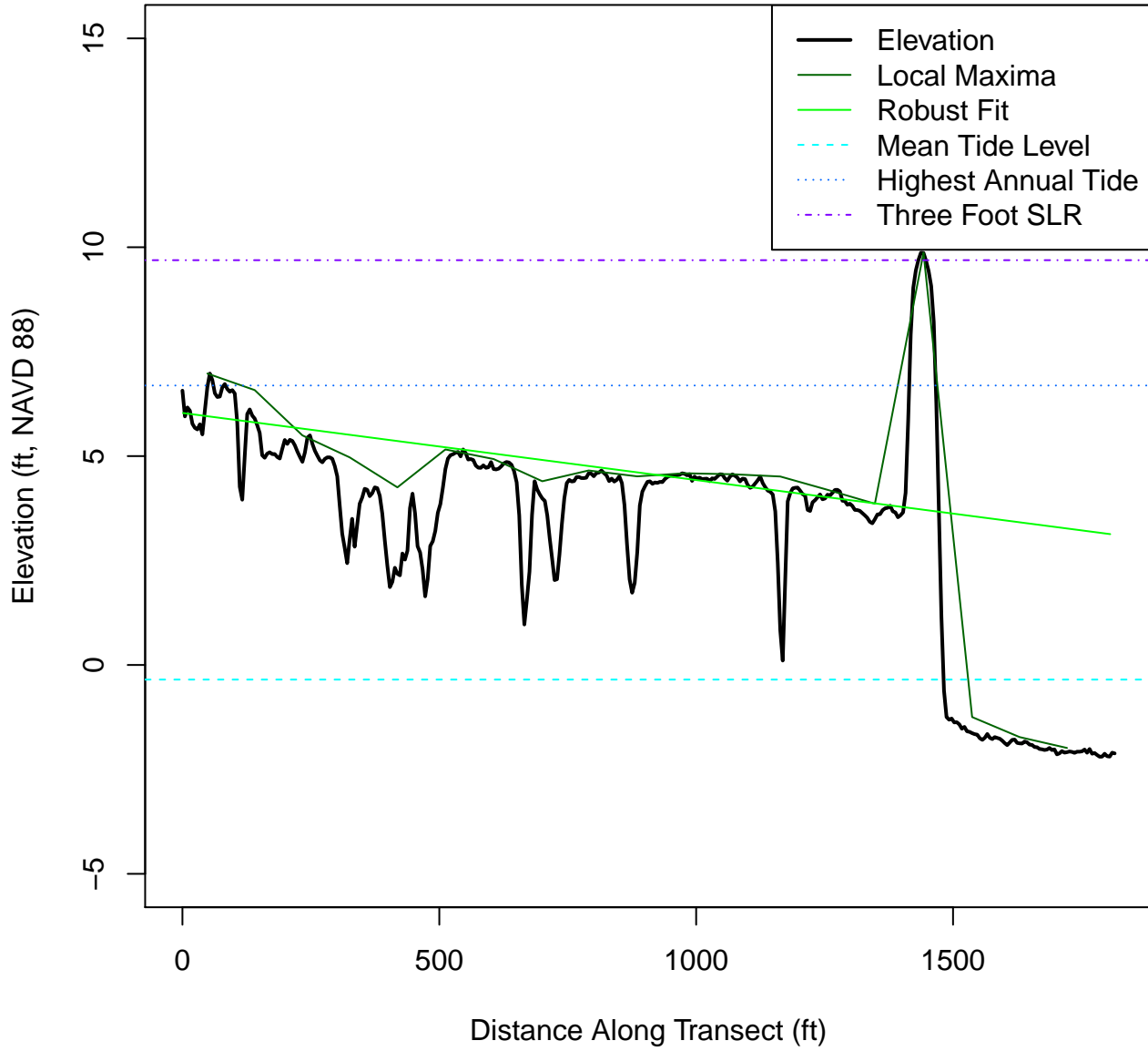
**Longitudinal Profile
TR70
Window = 9**



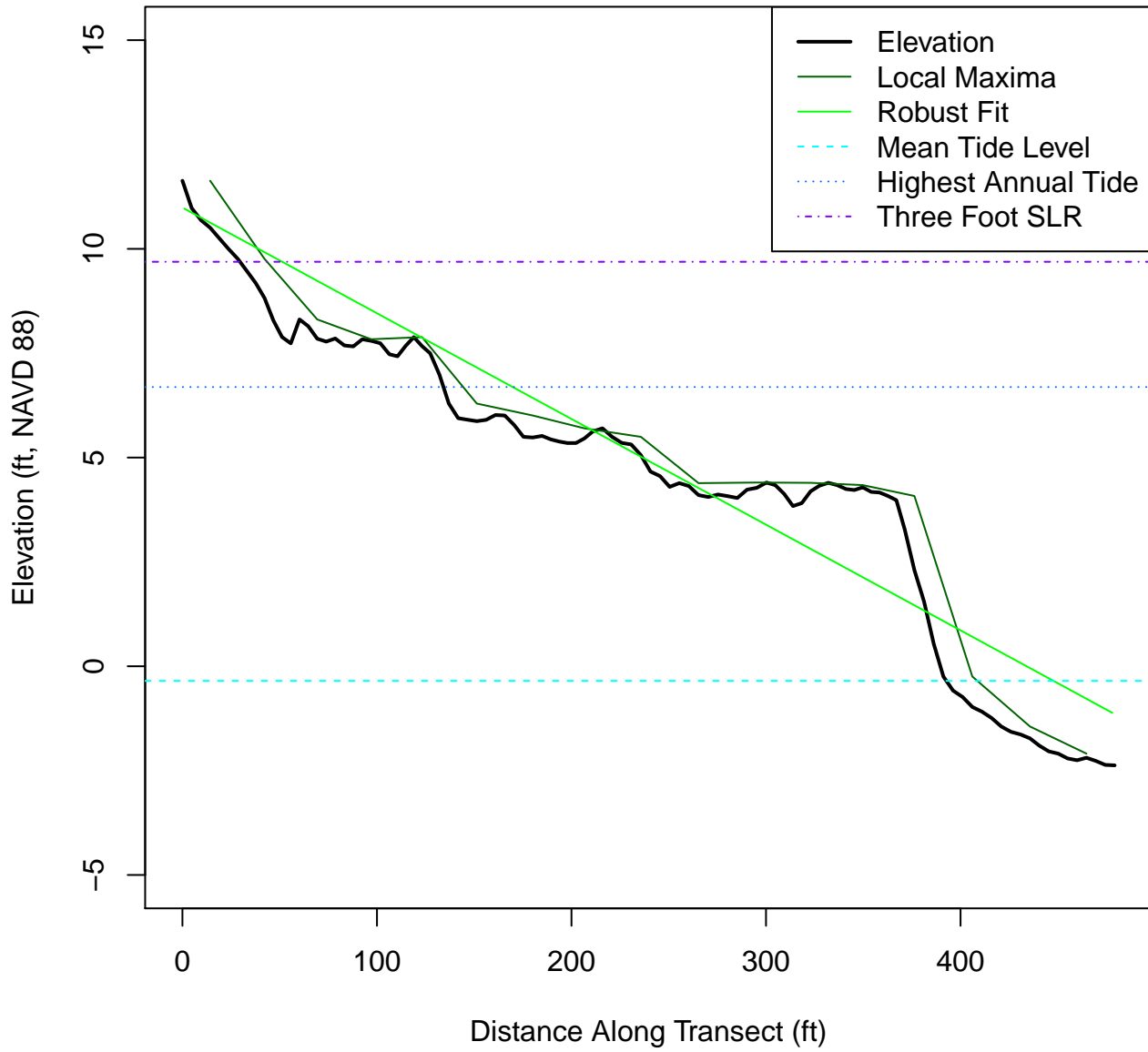
**Longitudinal Profile
TR71
Window = 5**



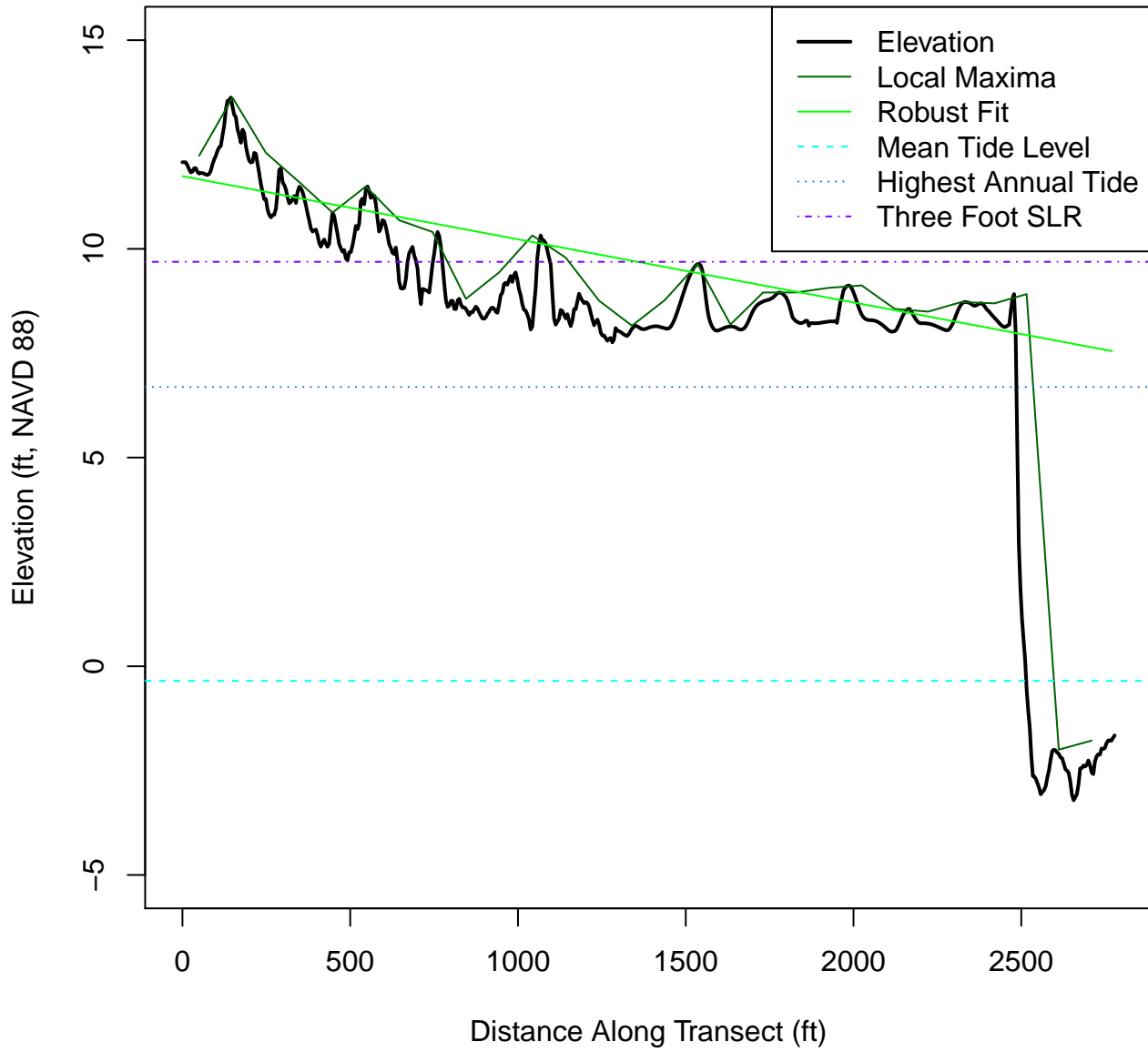
**Longitudinal Profile
TR72
Window = 19**



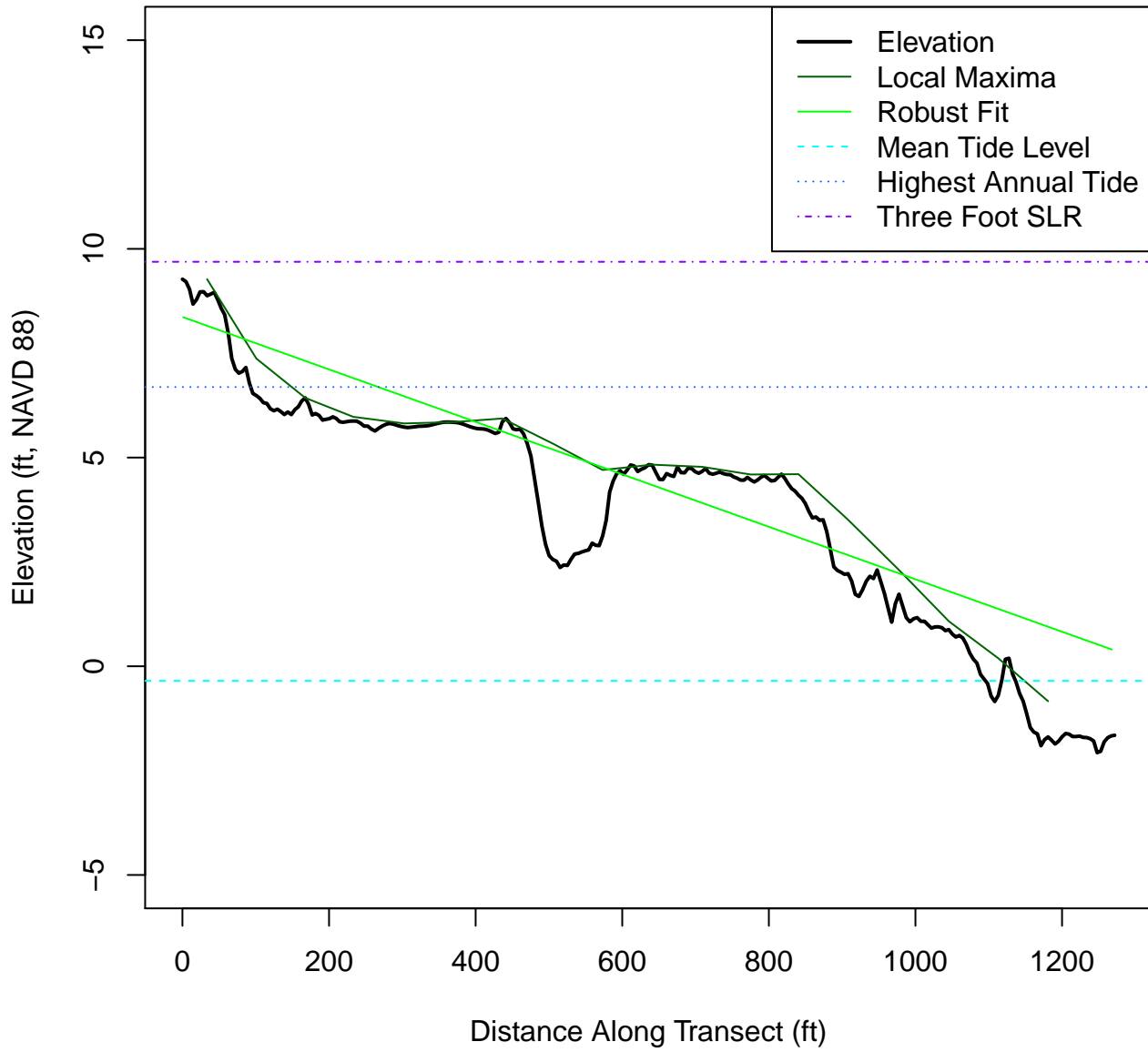
**Longitudinal Profile
TR73
Window = 6**



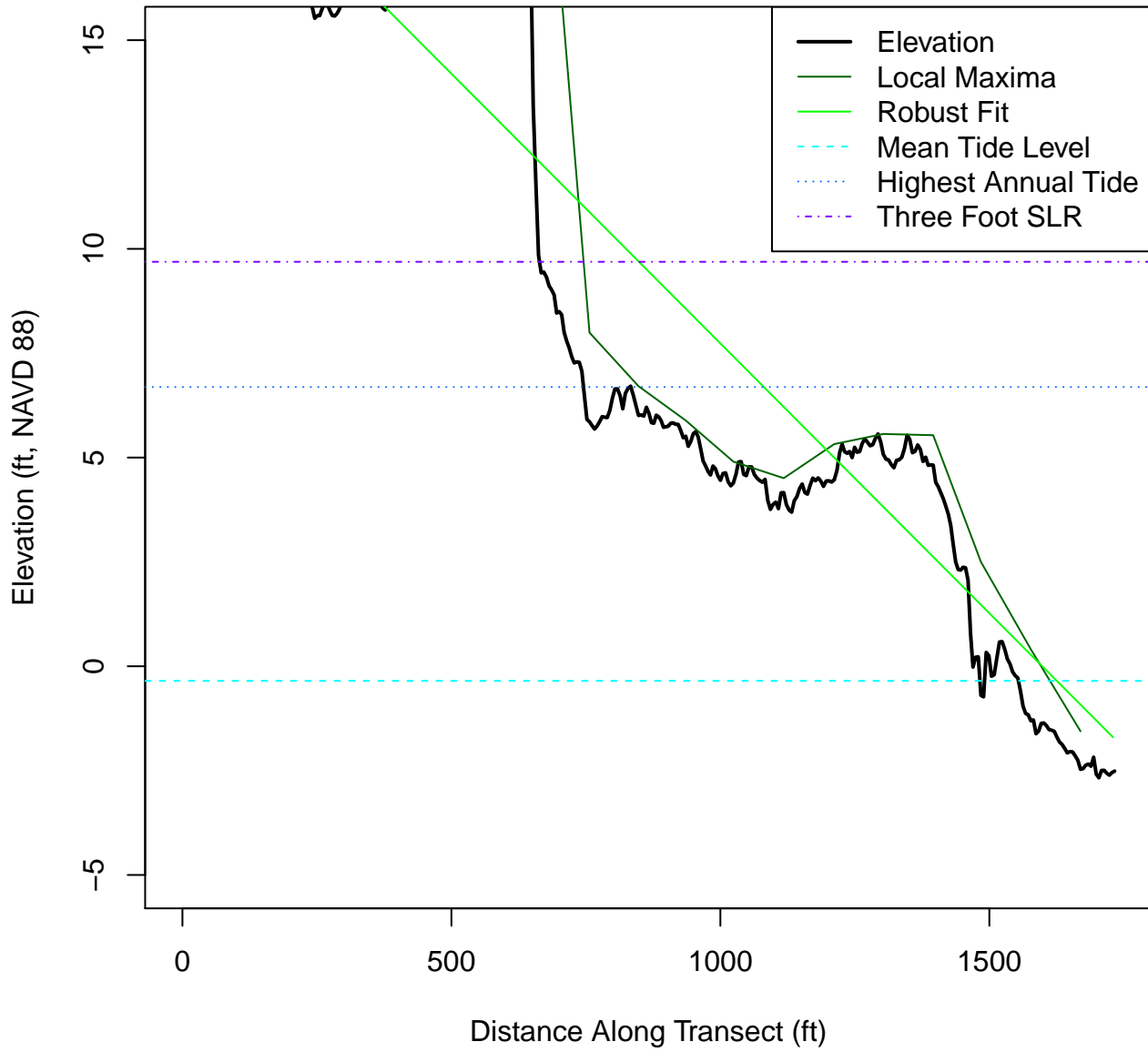
**Longitudinal Profile
TR74
Window = 20**



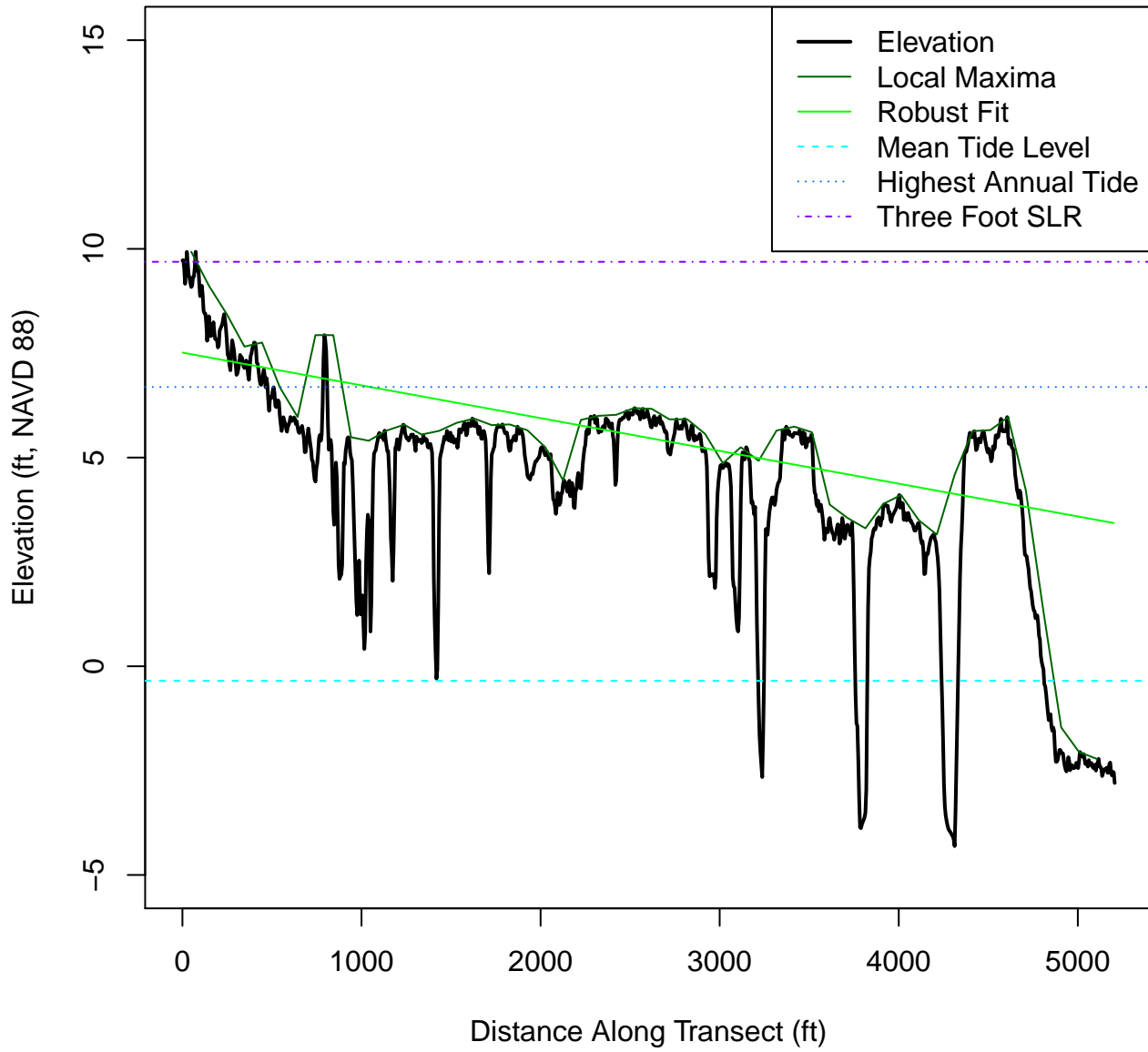
**Longitudinal Profile
TR75
Window = 14**



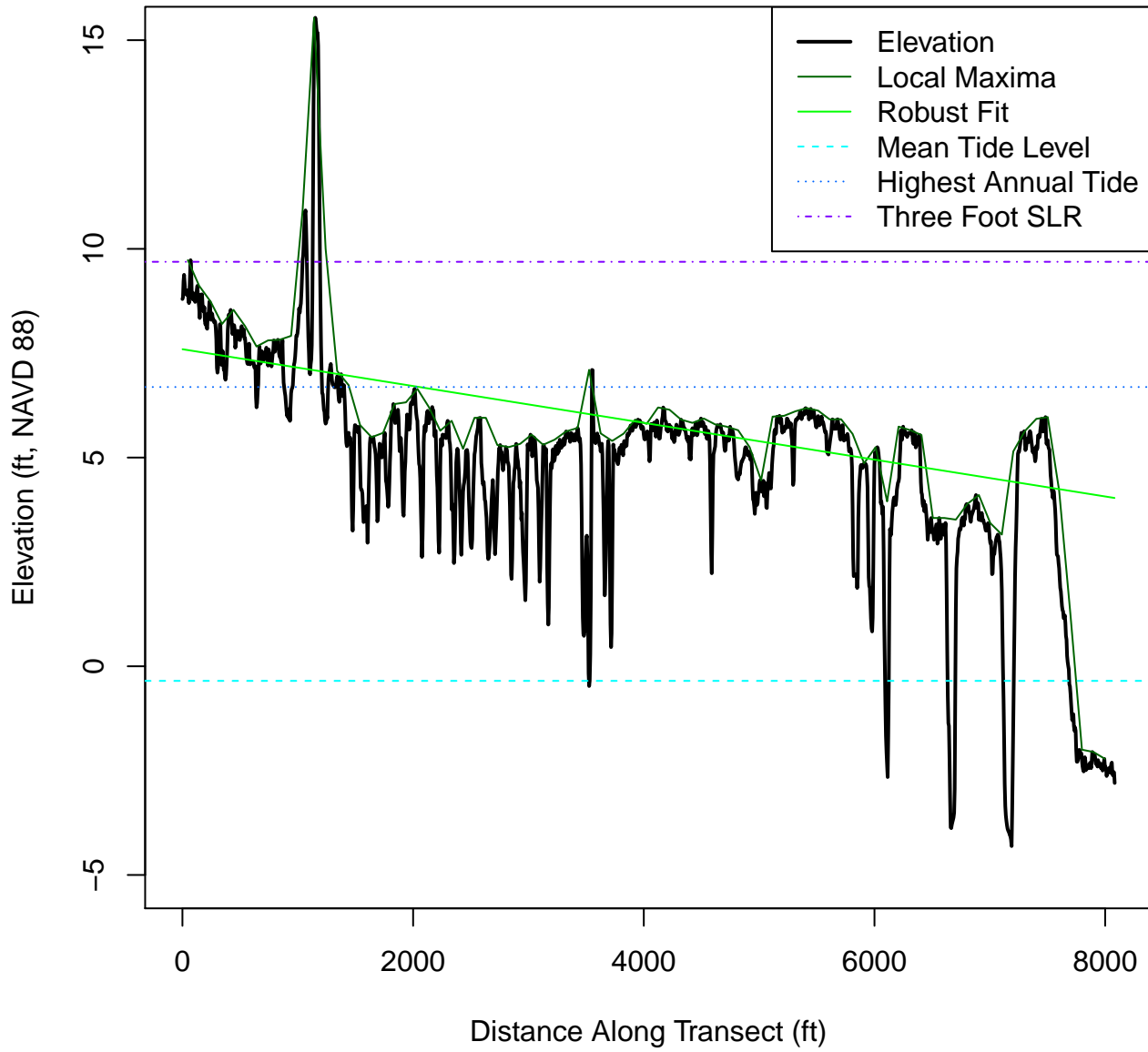
**Longitudinal Profile
TR76
Window = 19**



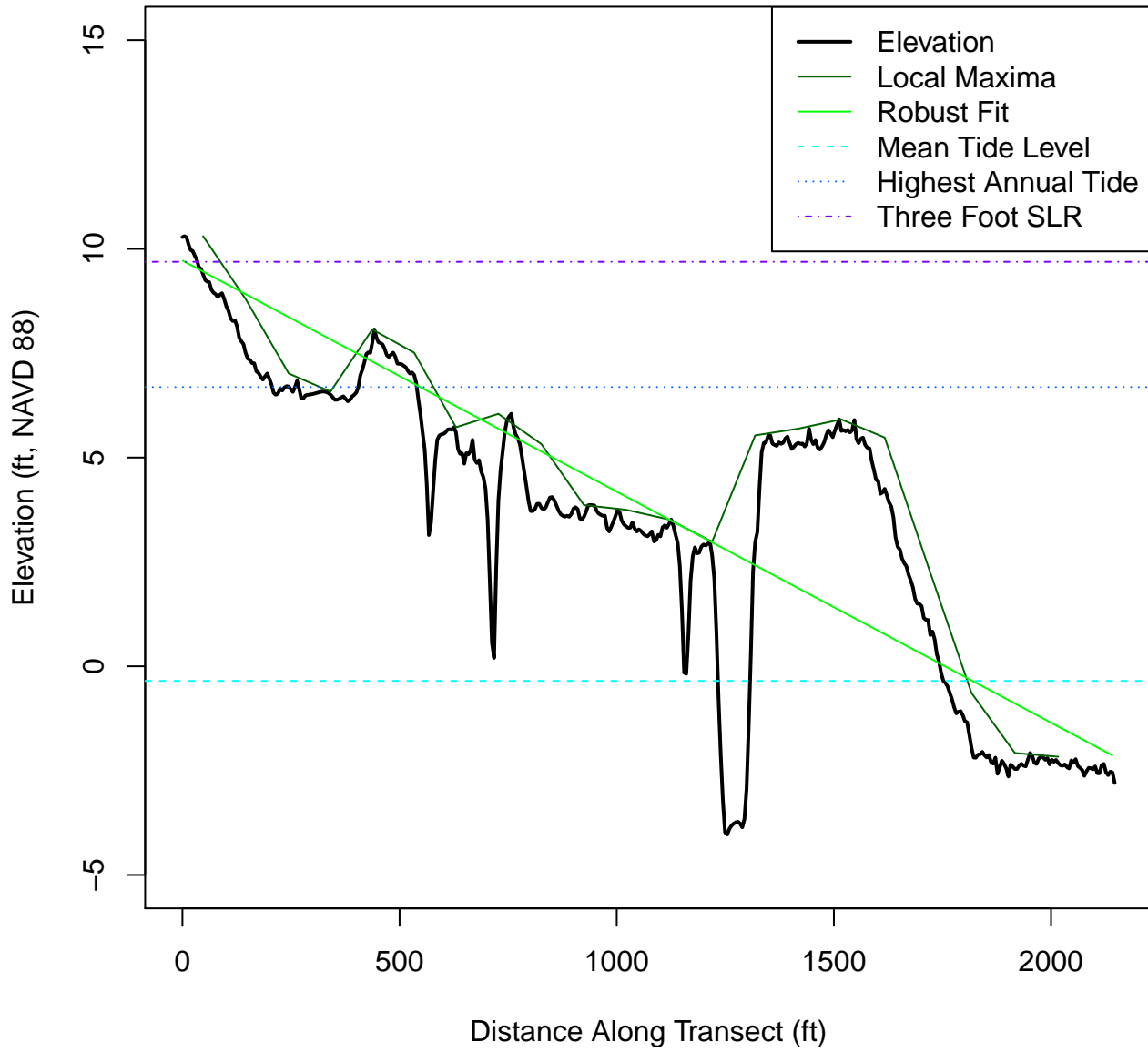
**Longitudinal Profile
TR77
Window = 20**



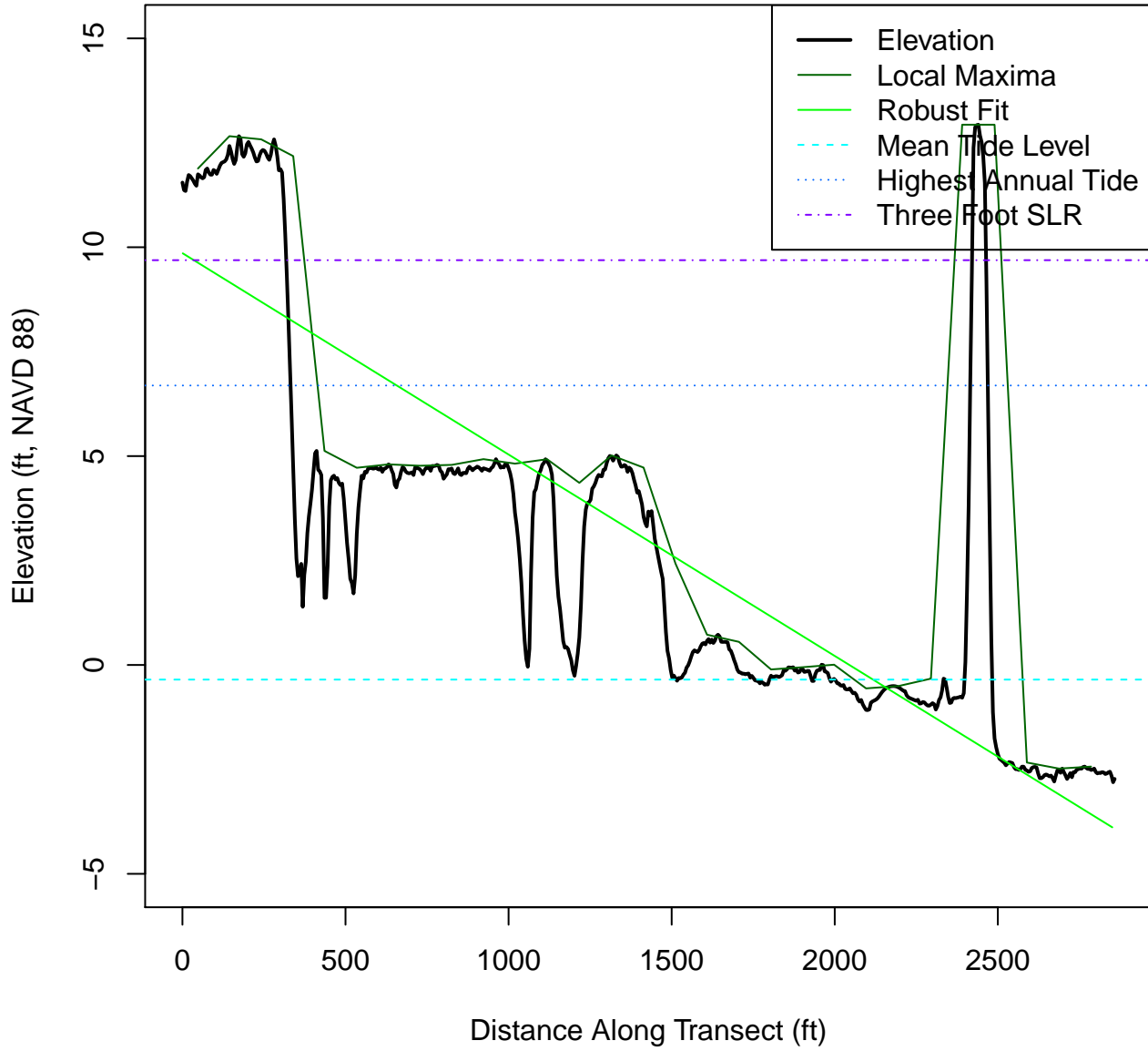
**Longitudinal Profile
TR78
Window = 20**



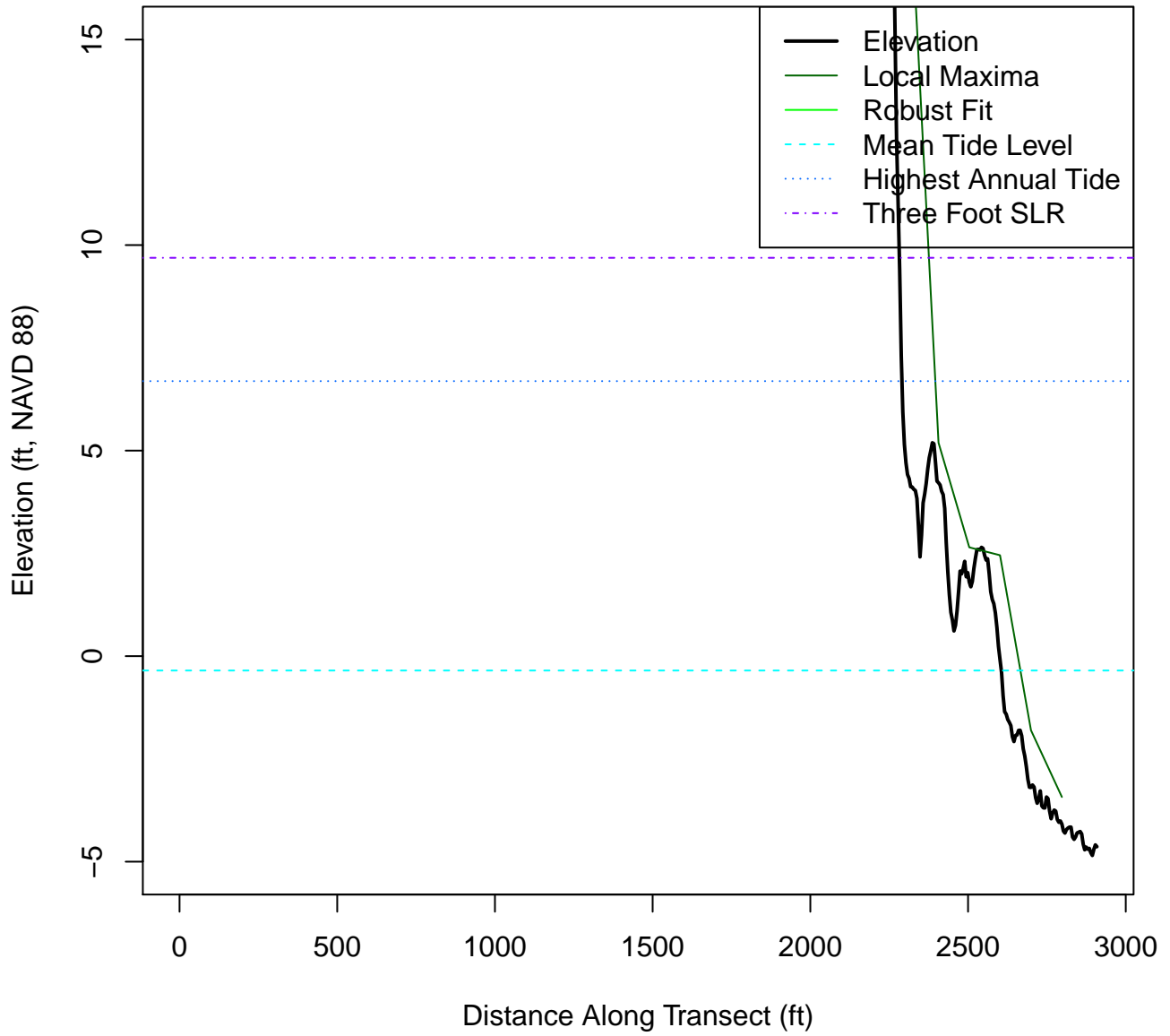
**Longitudinal Profile
TR79
Window = 20**



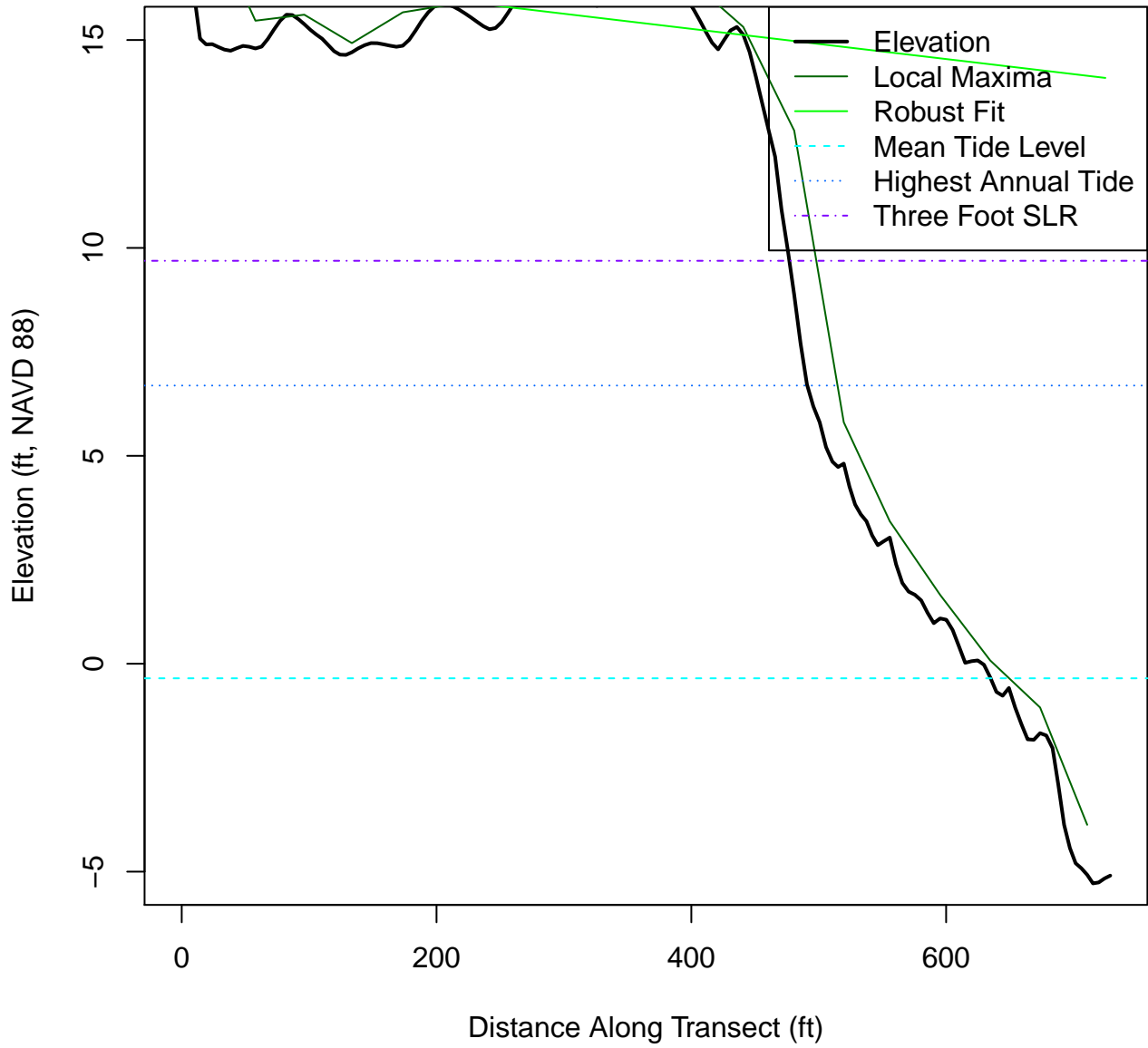
**Longitudinal Profile
TR80
Window = 20**



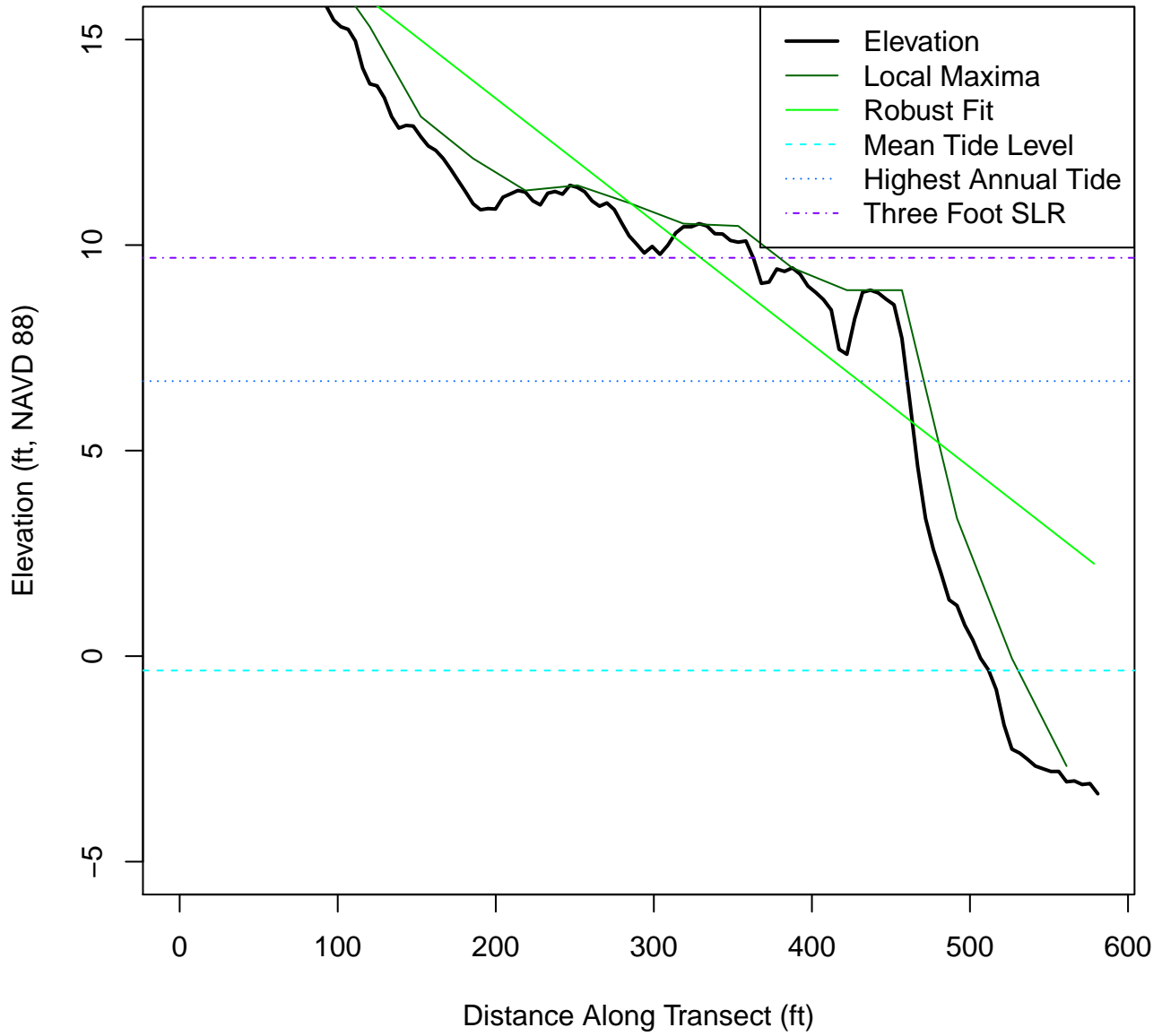
**Longitudinal Profile
TR81
Window = 20**



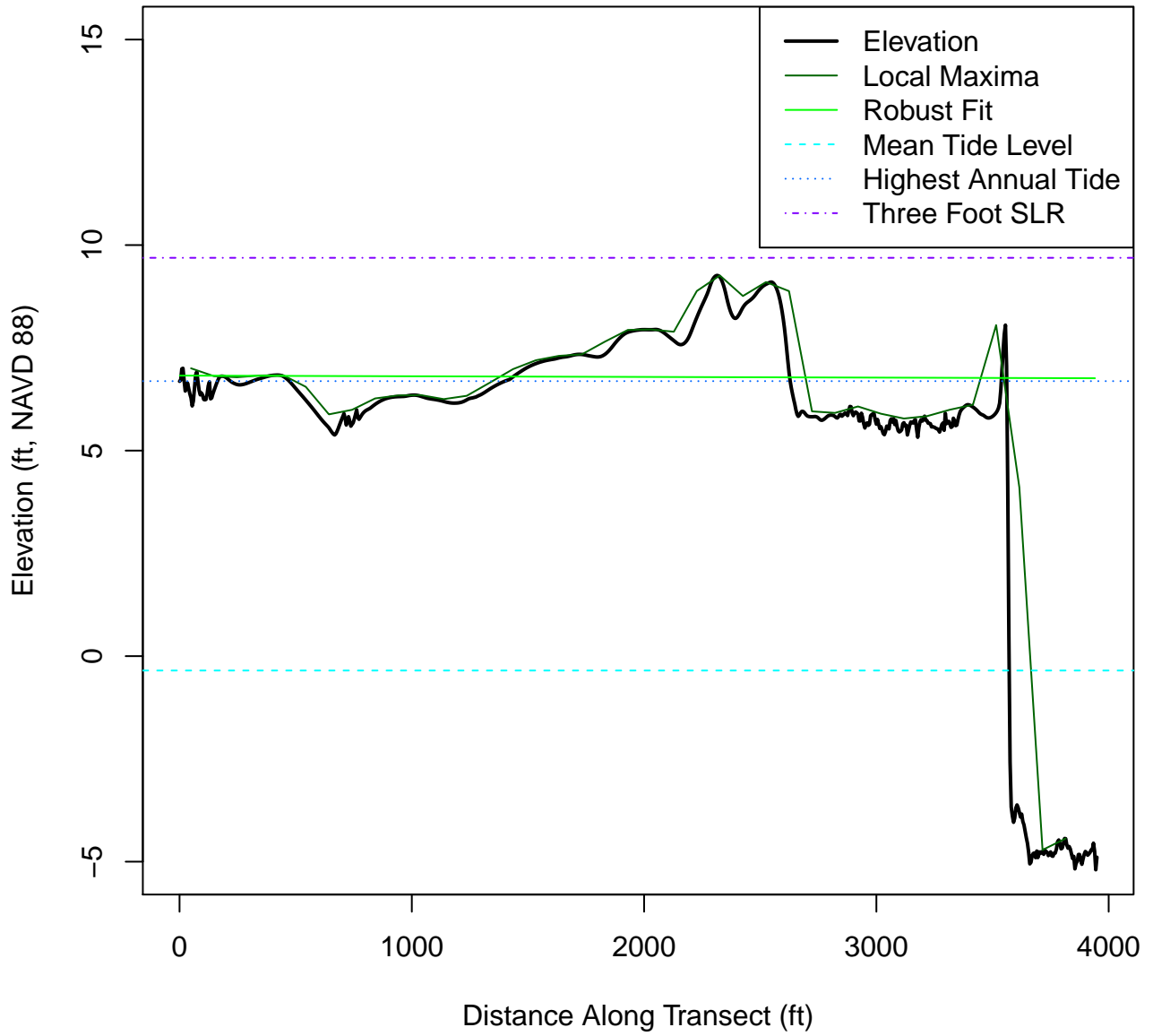
**Longitudinal Profile
TR82
Window = 8**



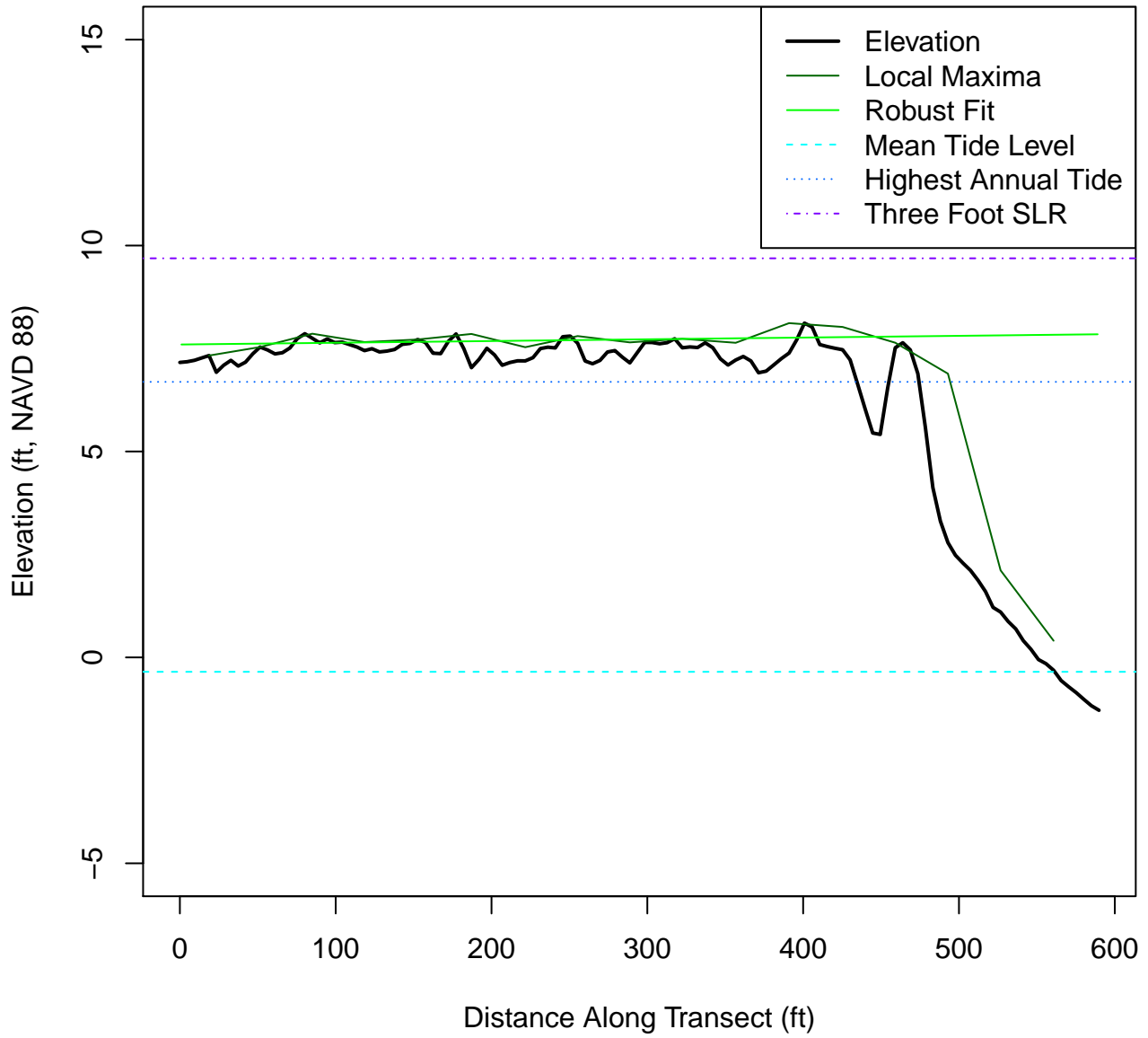
**Longitudinal Profile
TR84
Window = 7**



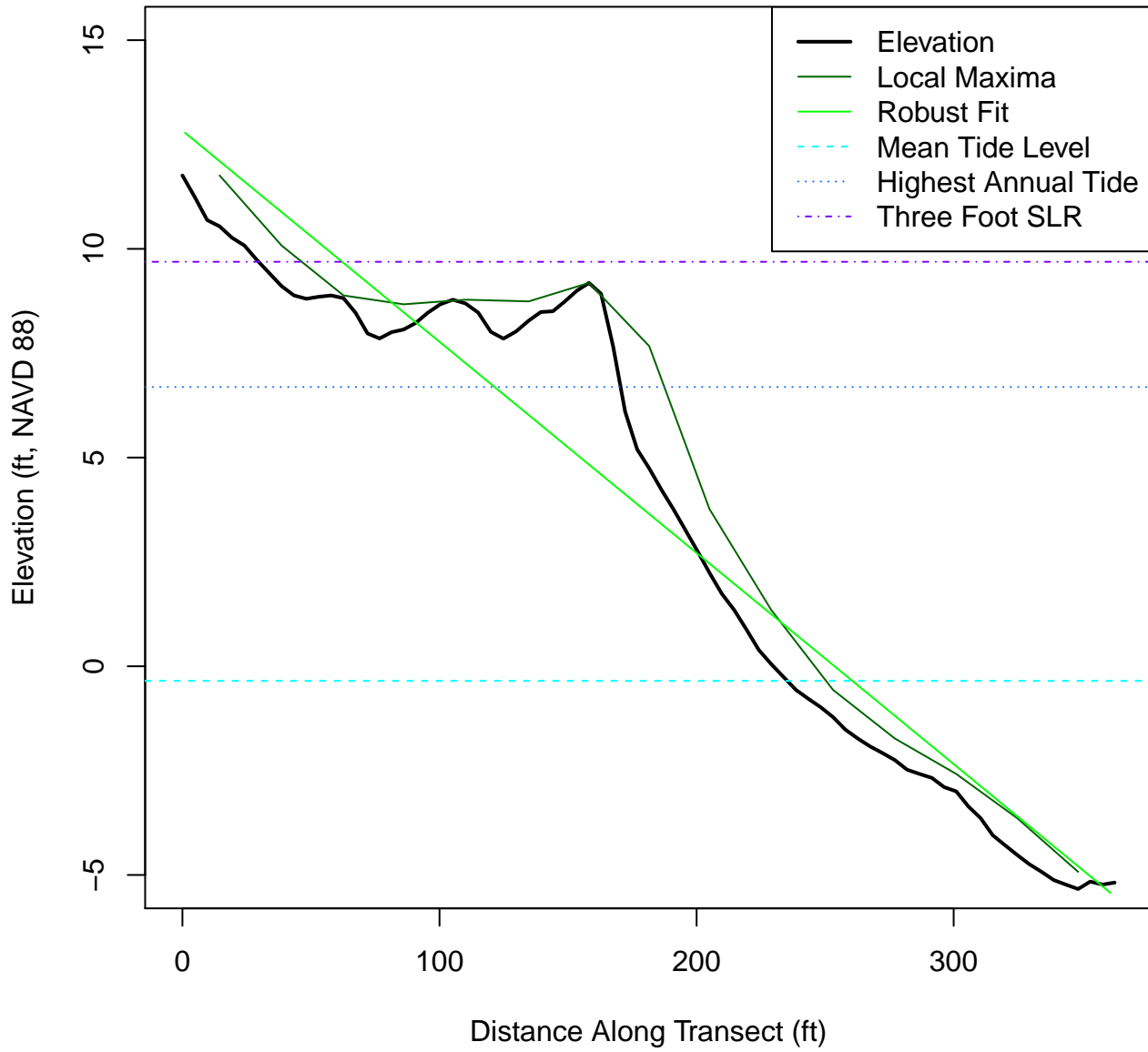
**Longitudinal Profile
TR85
Window = 20**



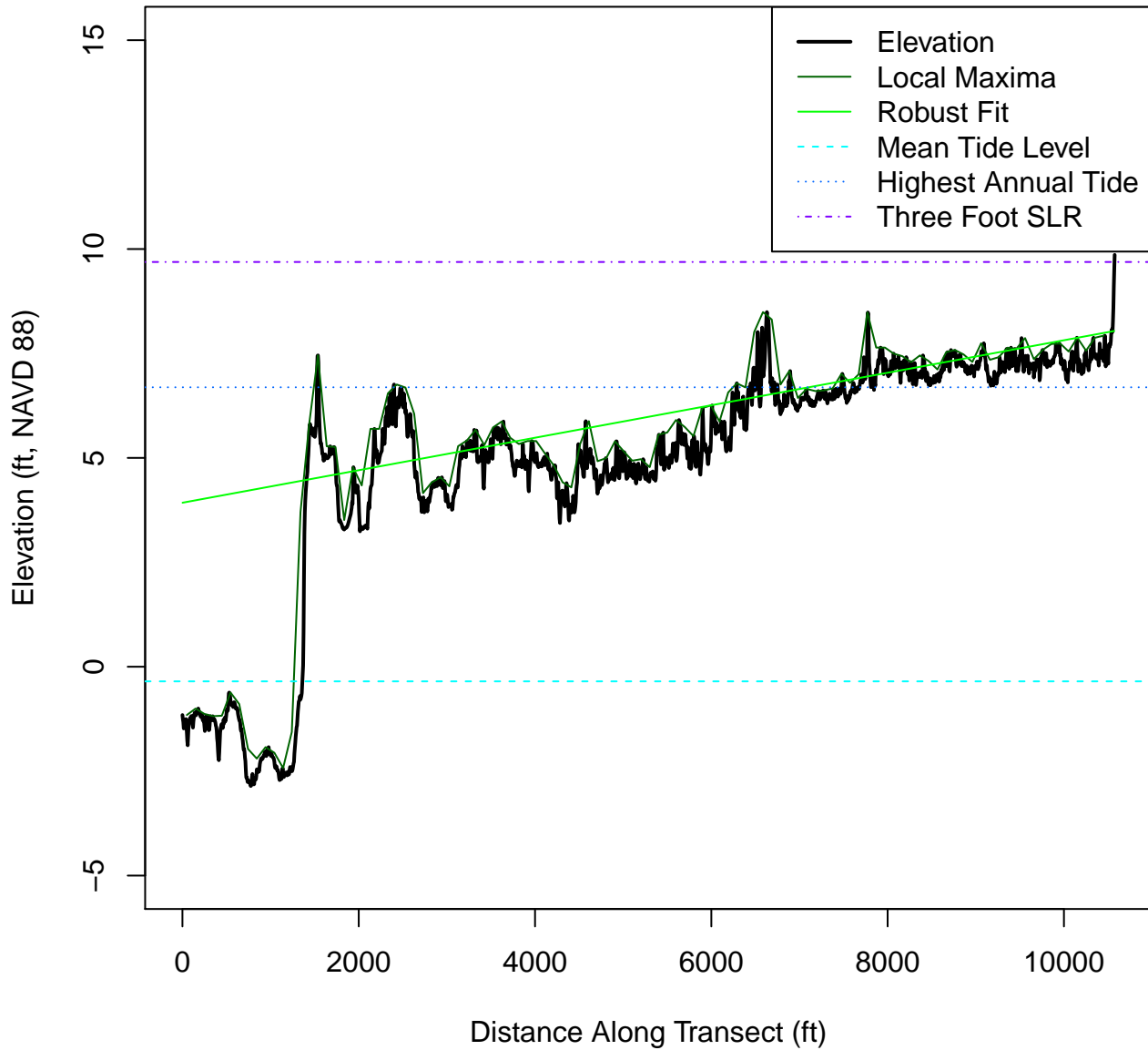
**Longitudinal Profile
TR86
Window = 7**



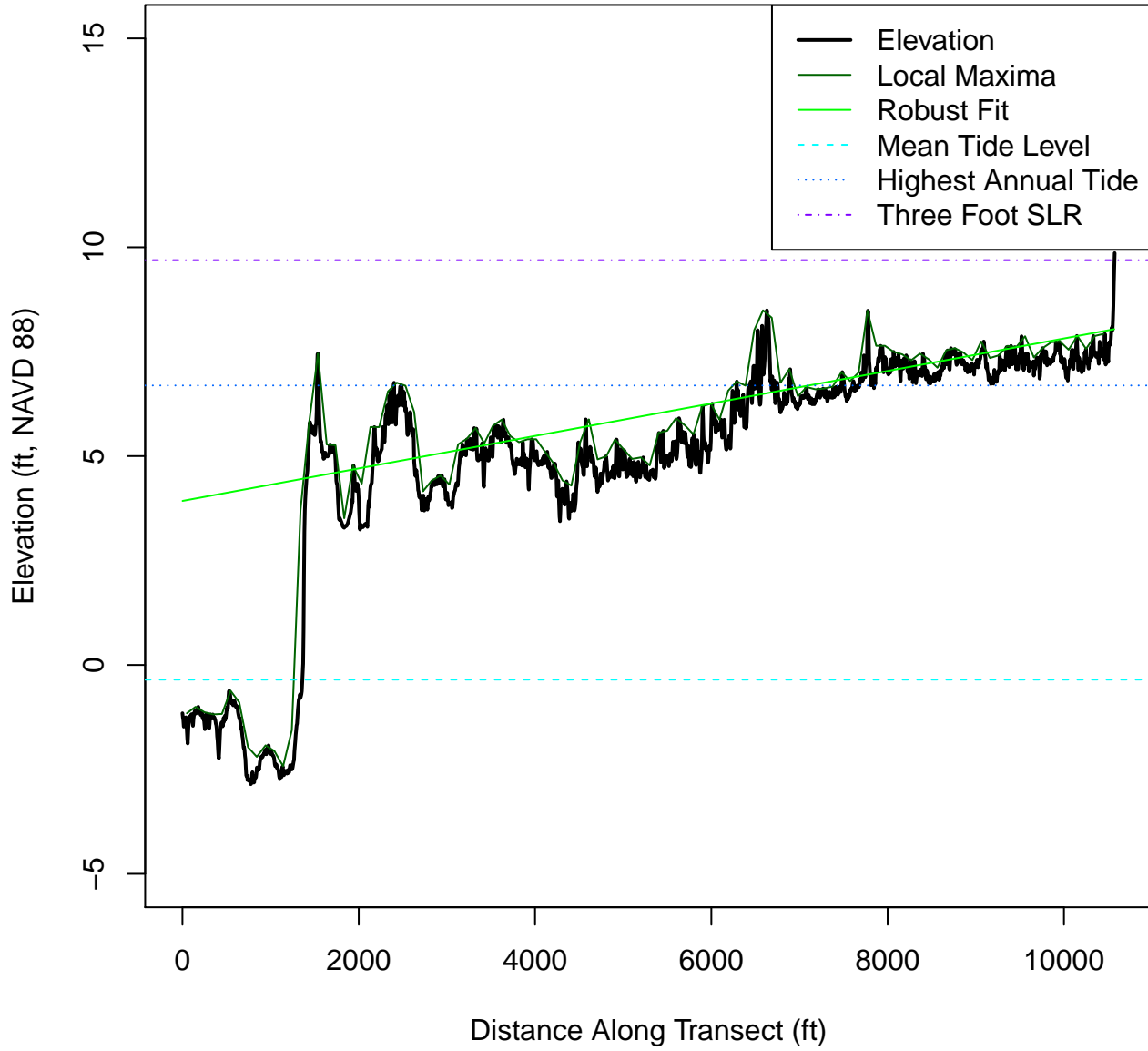
**Longitudinal Profile
TR87
Window = 5**



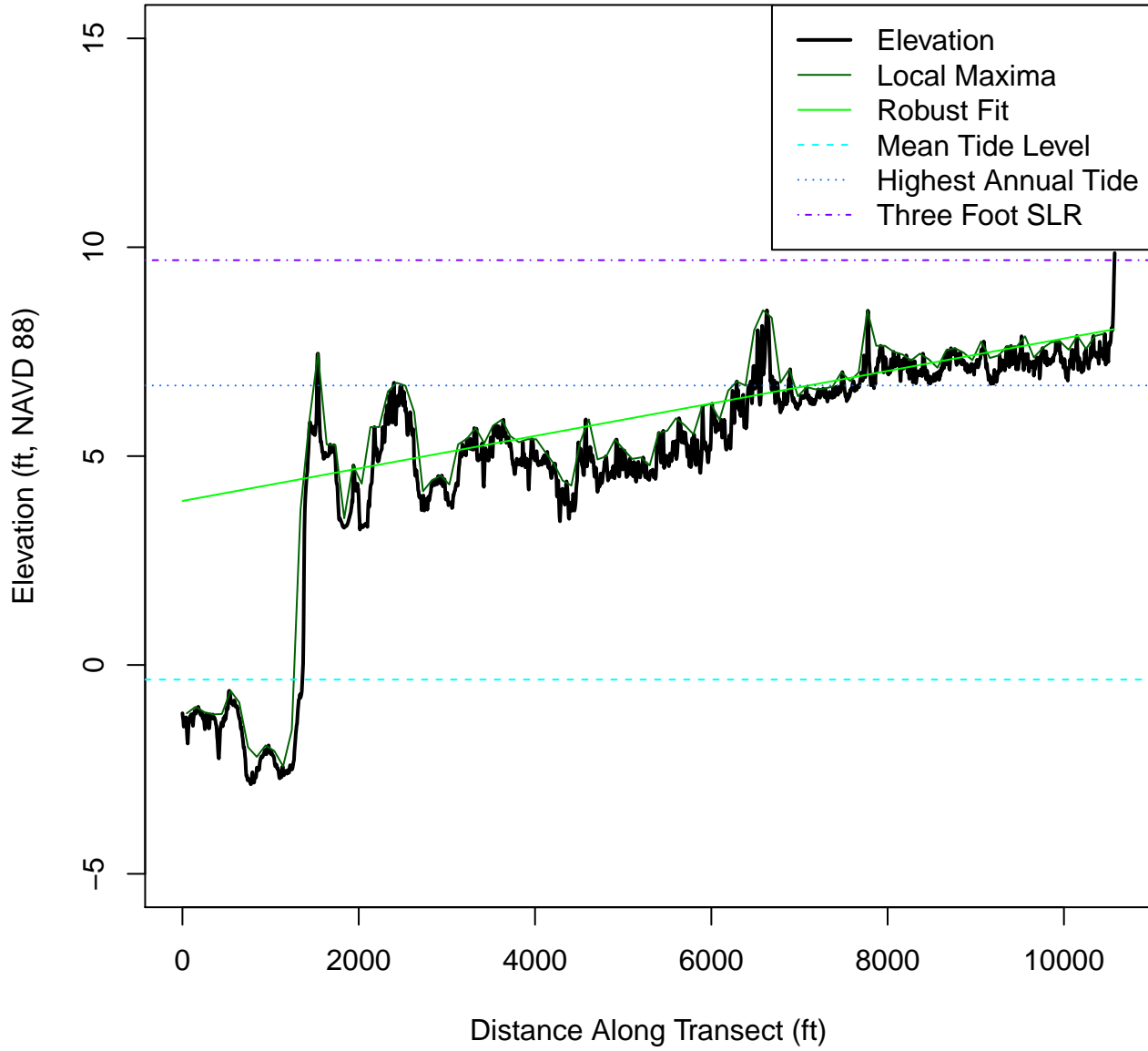
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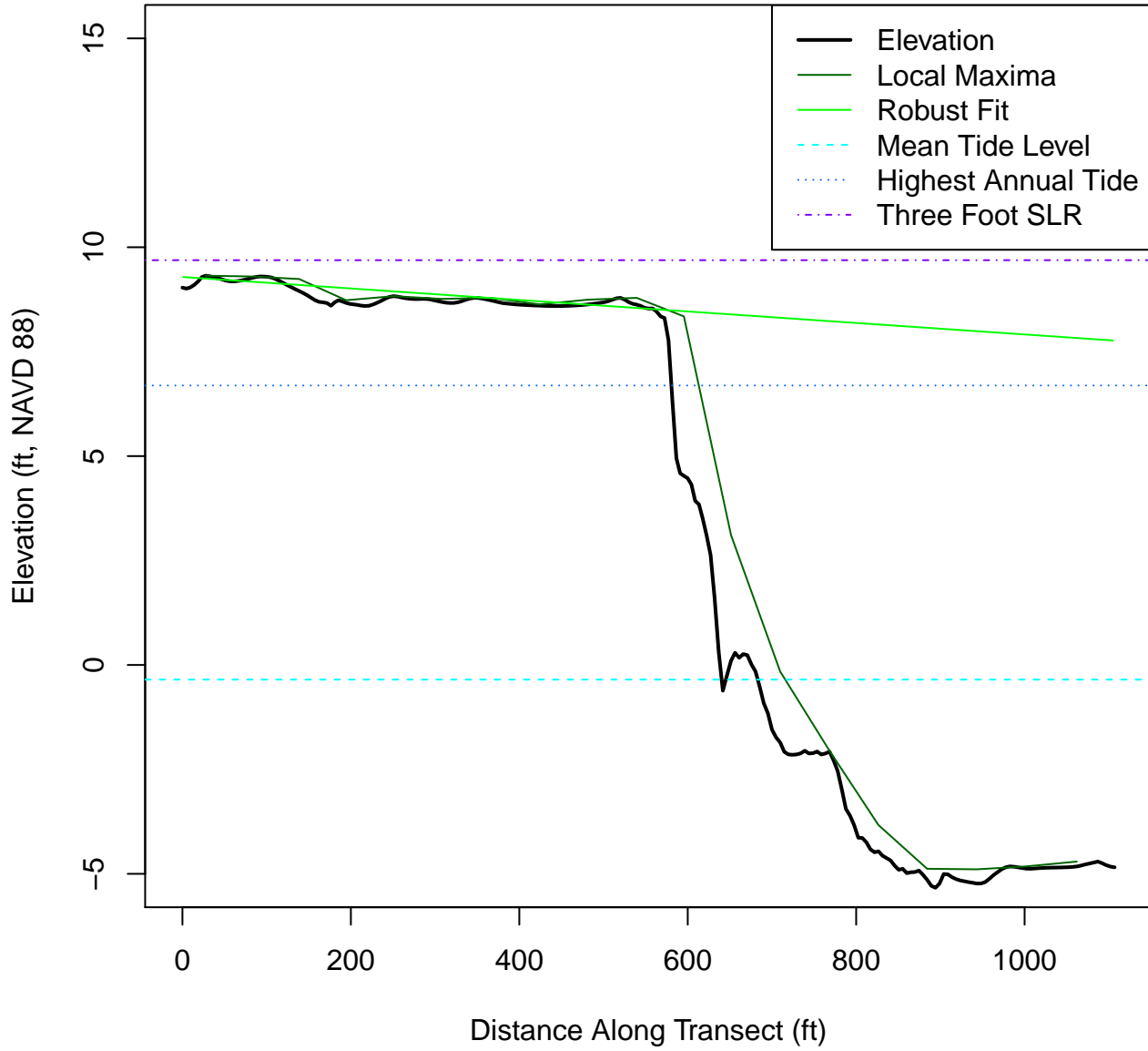
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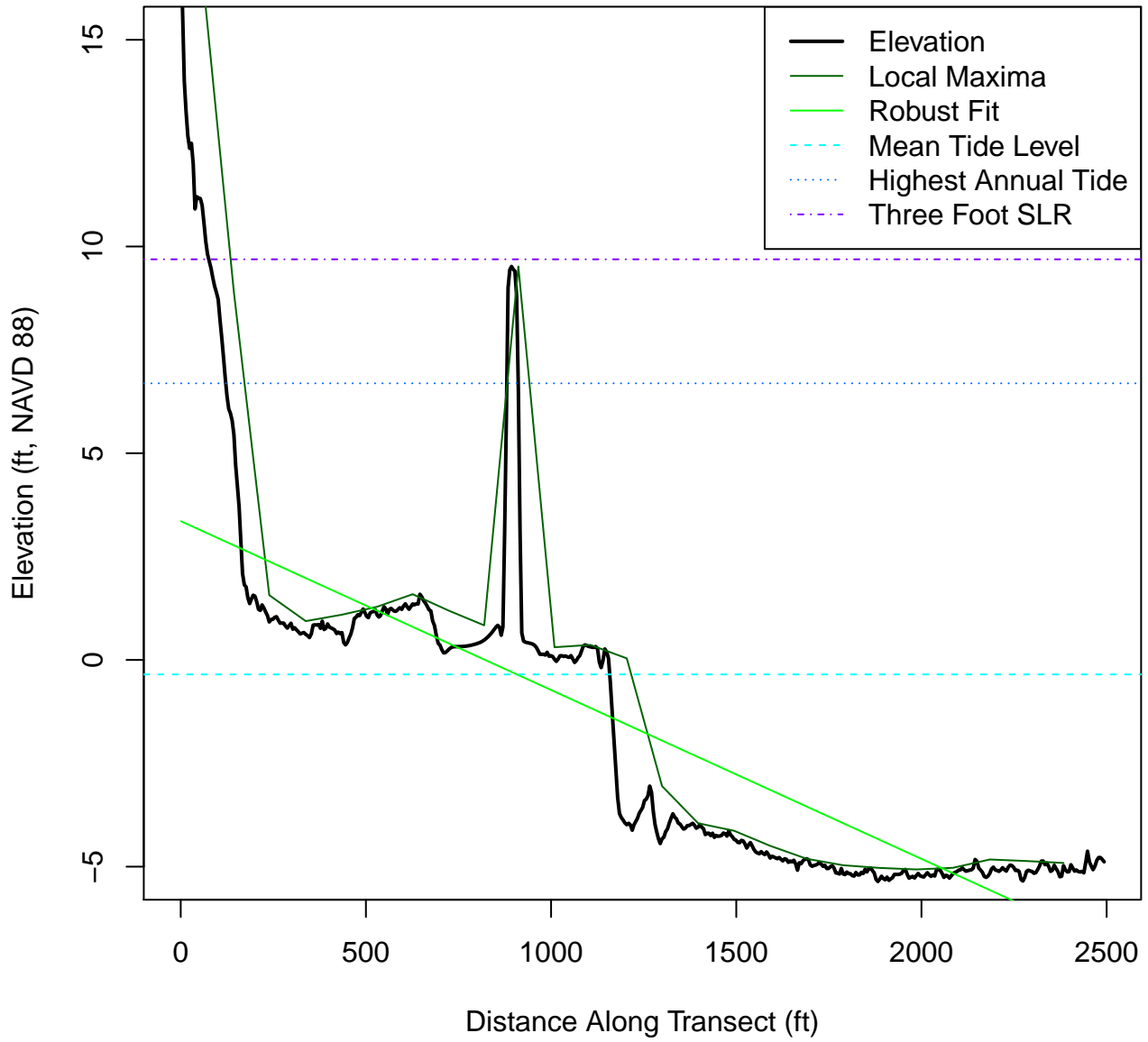
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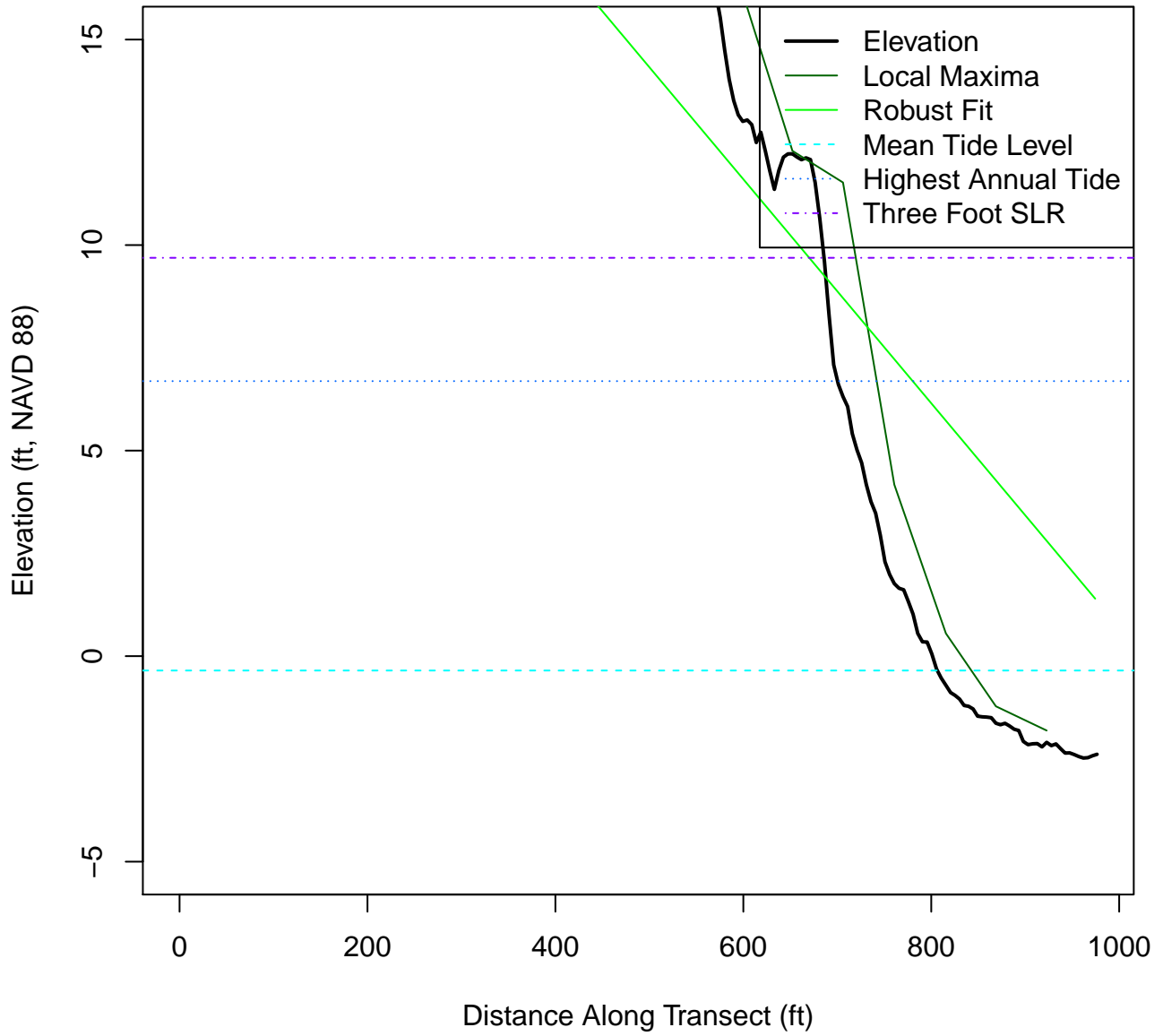
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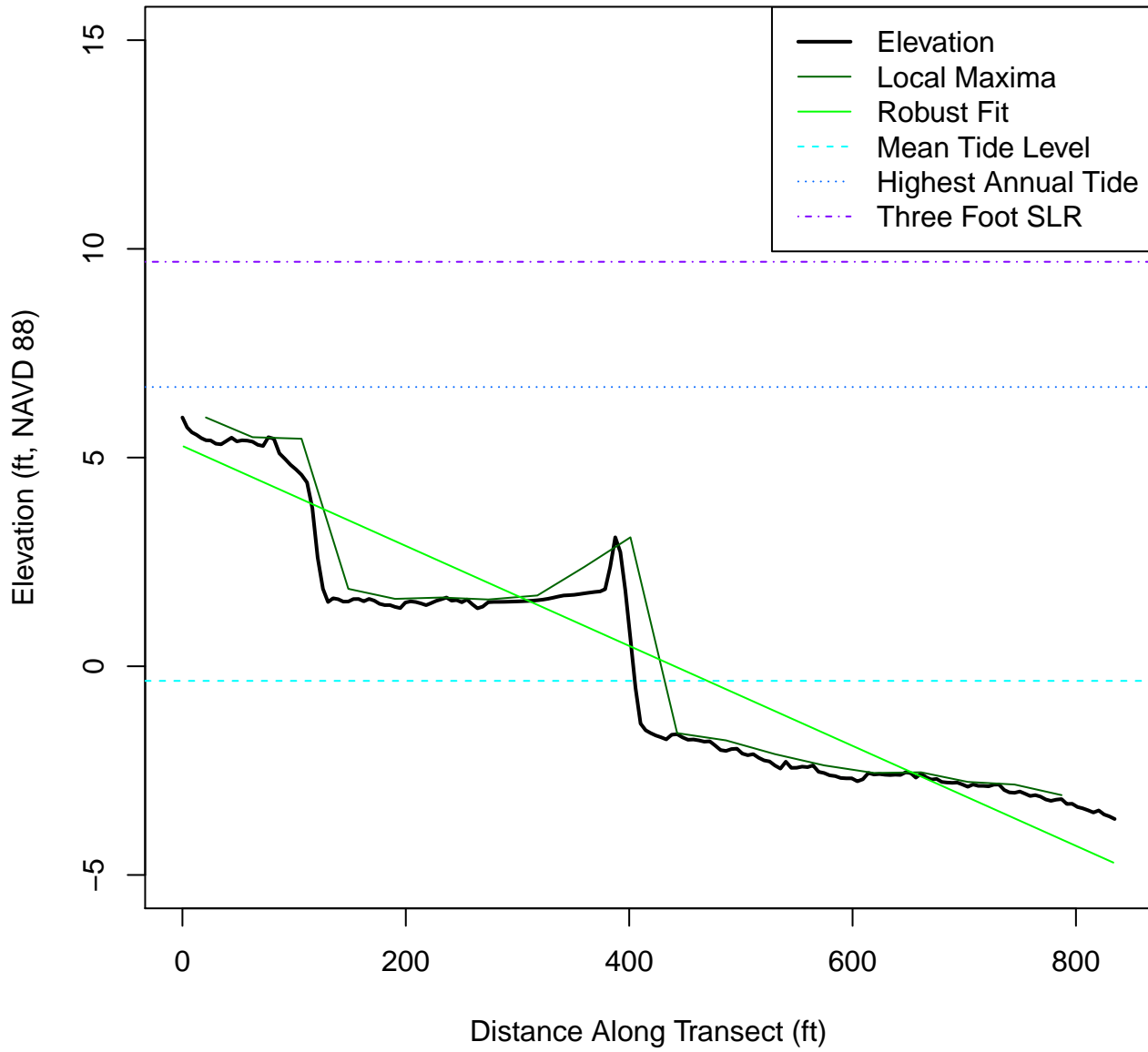
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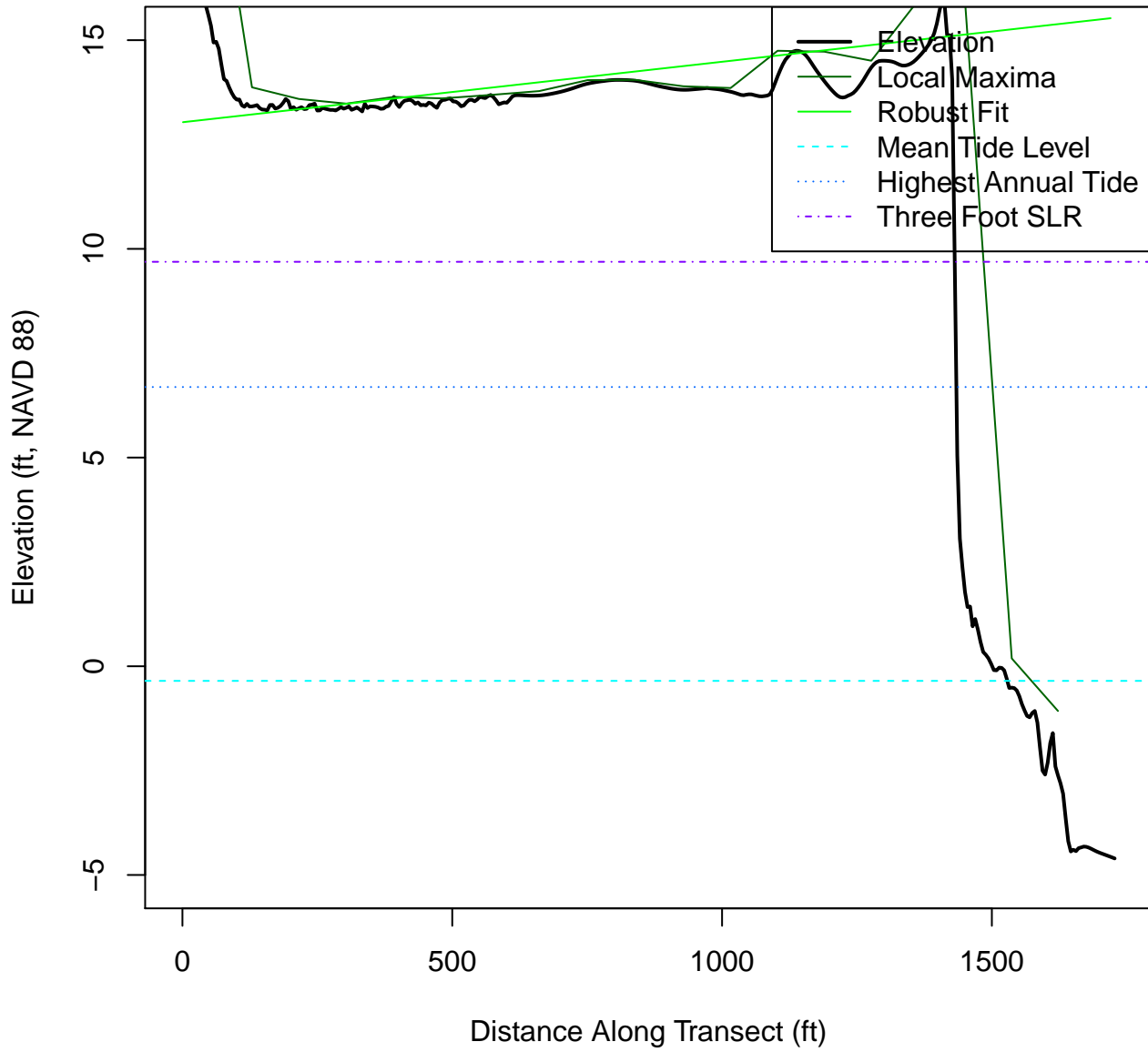
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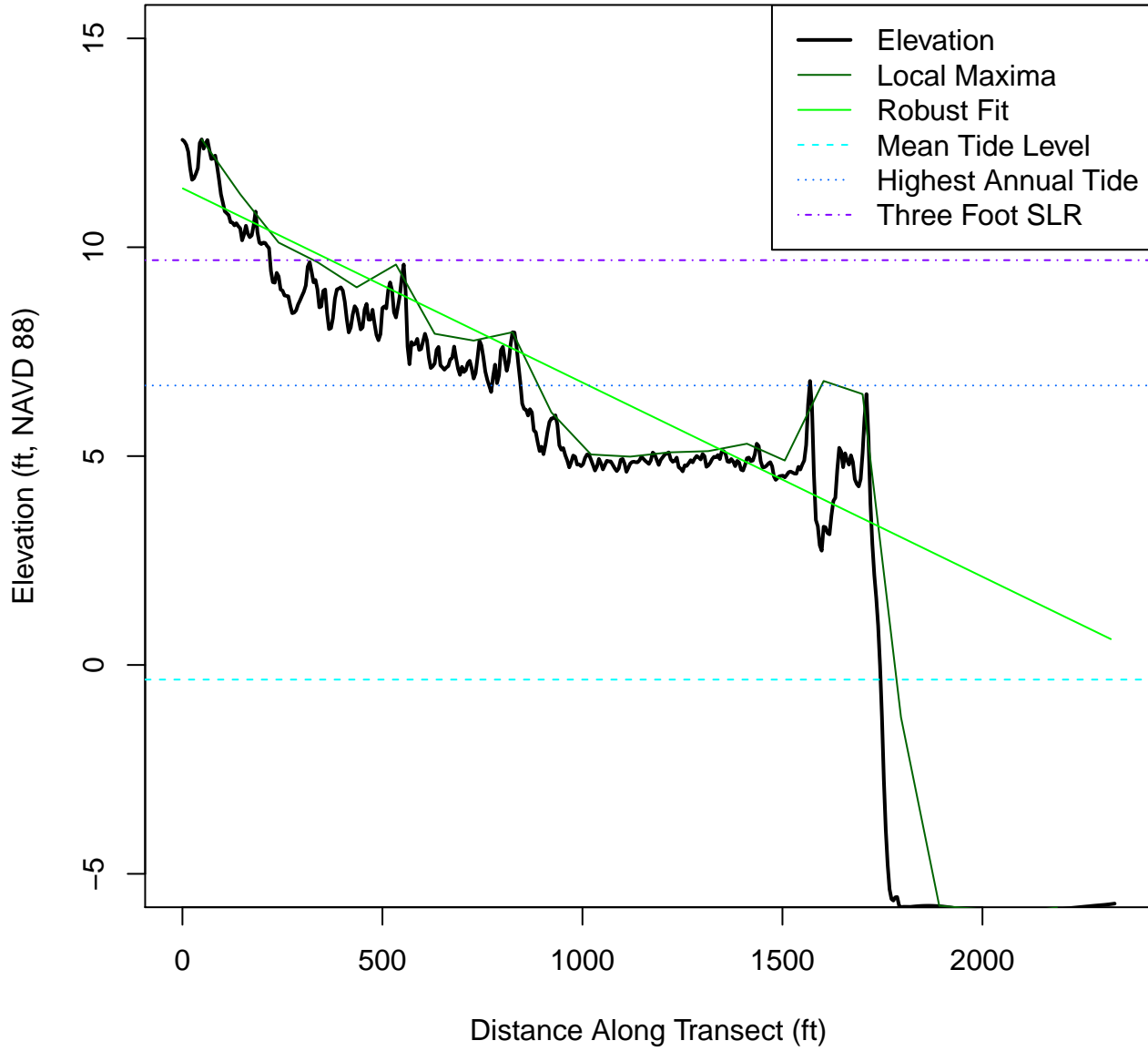
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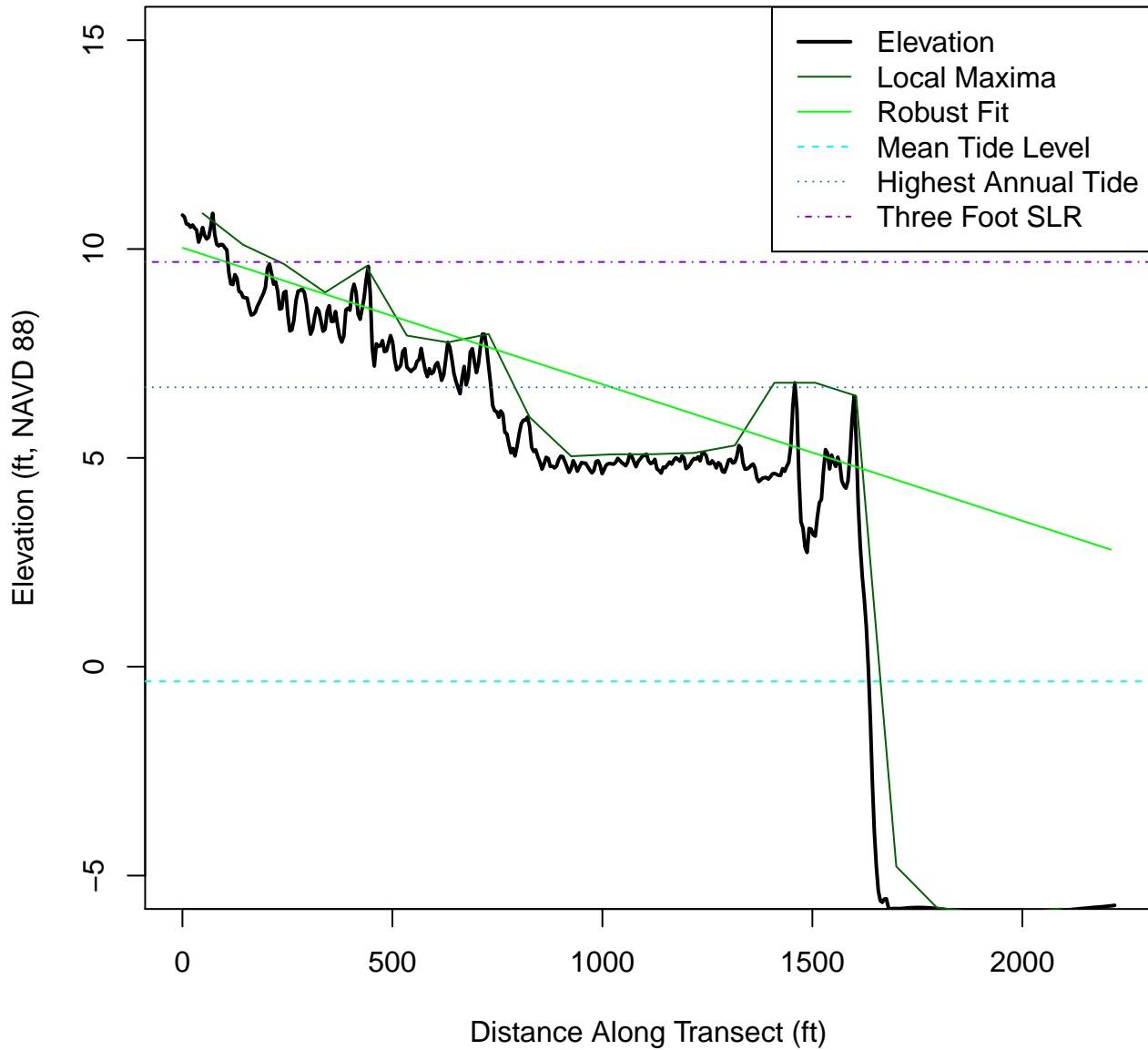
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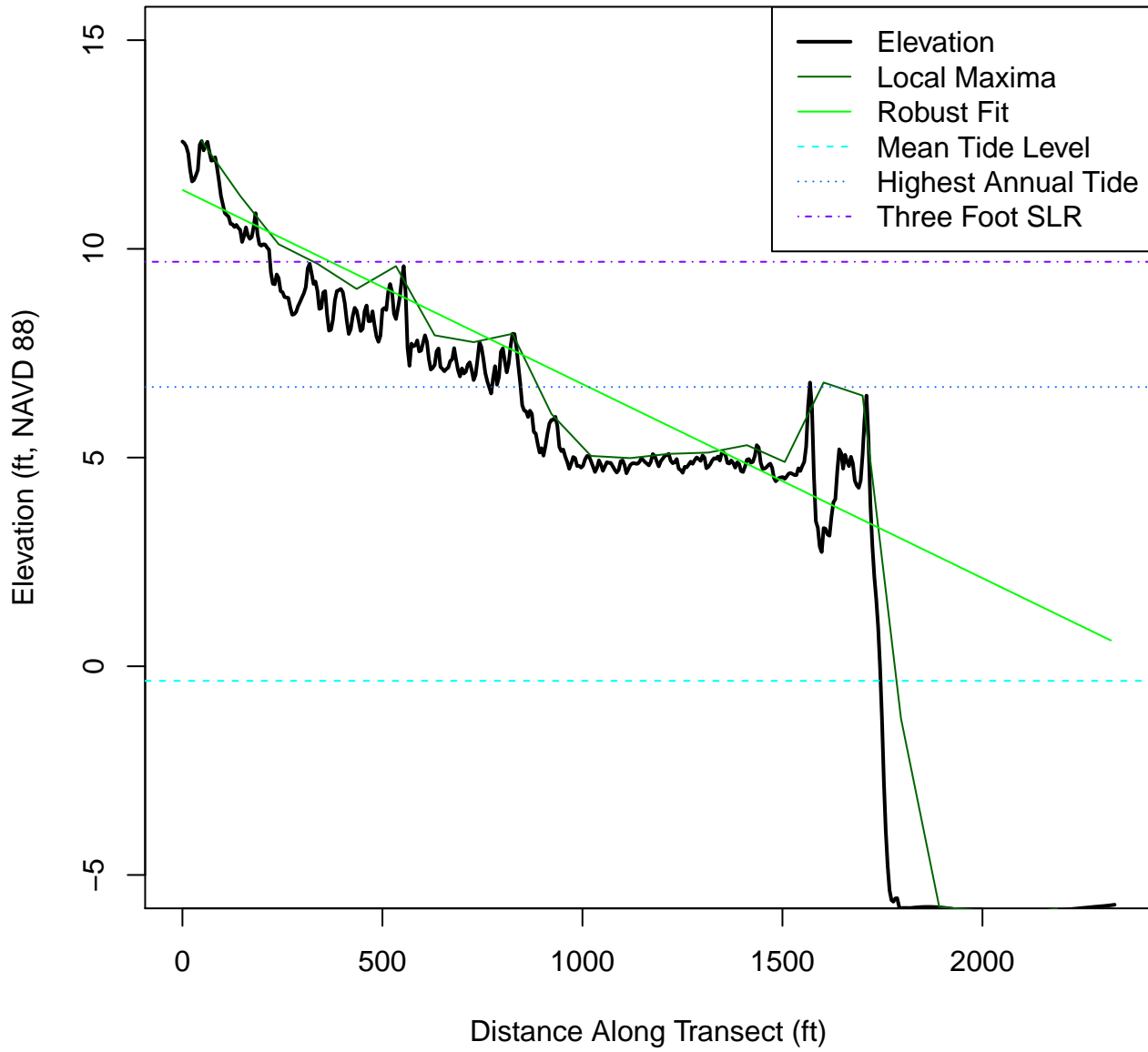
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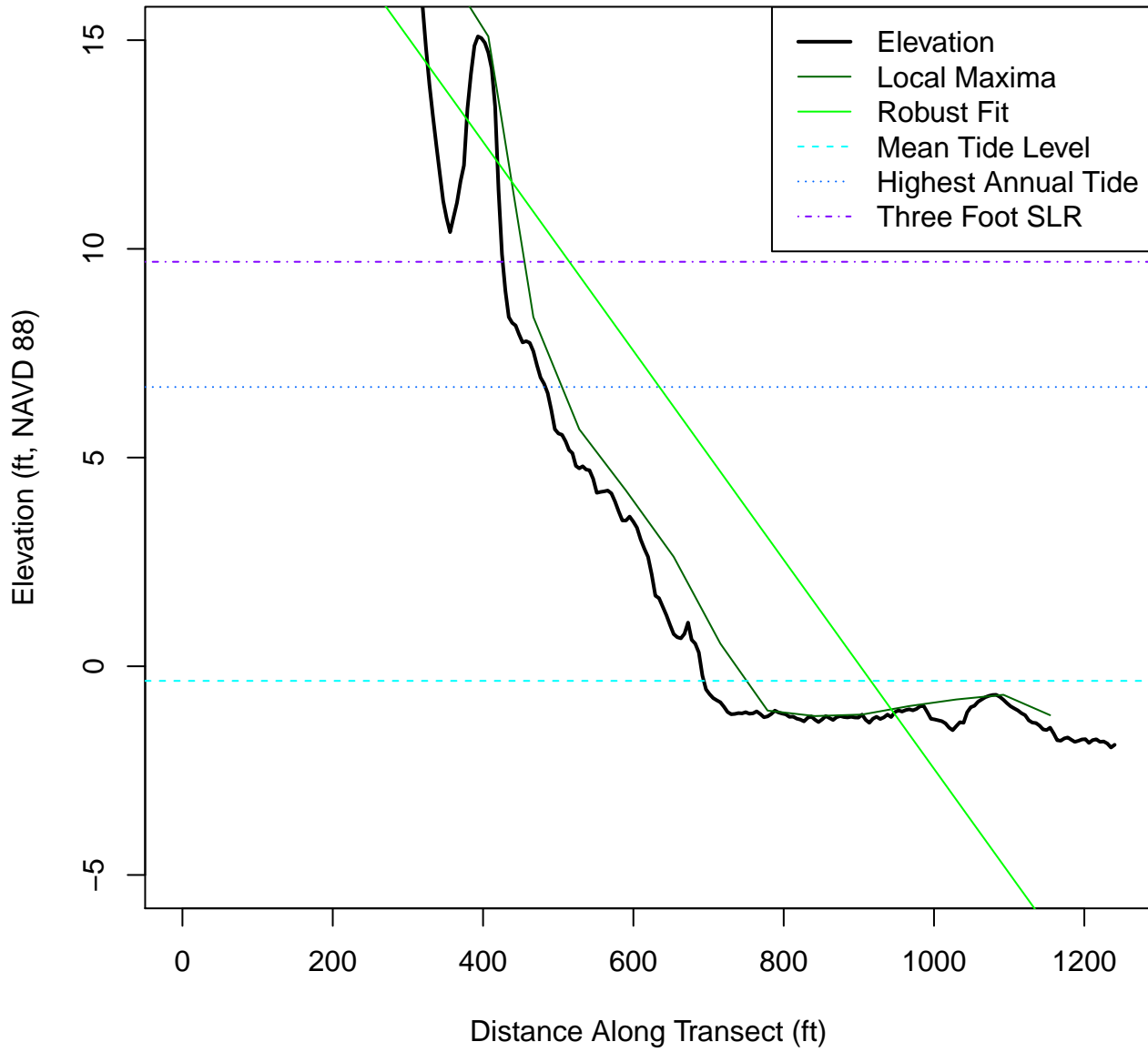
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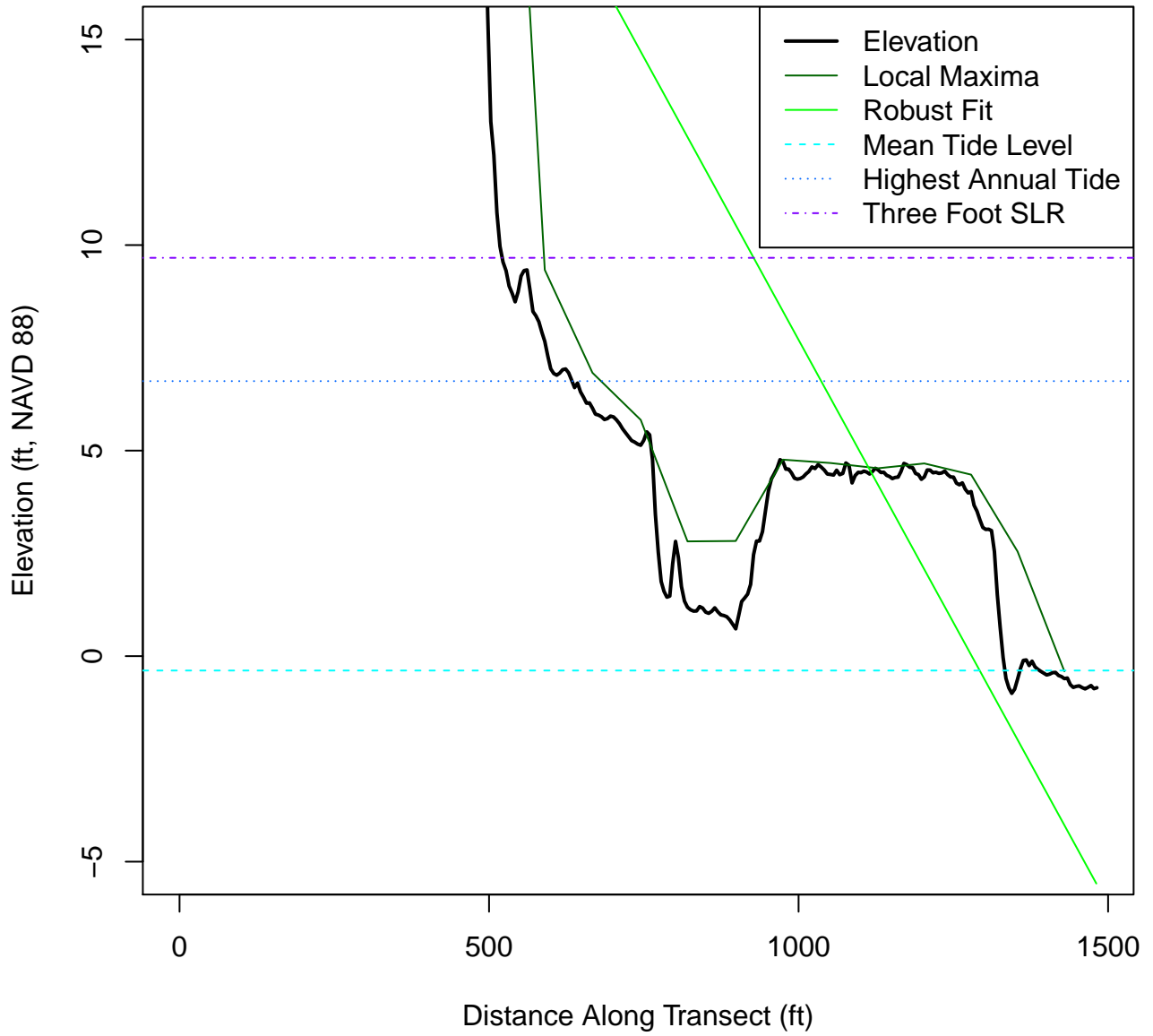
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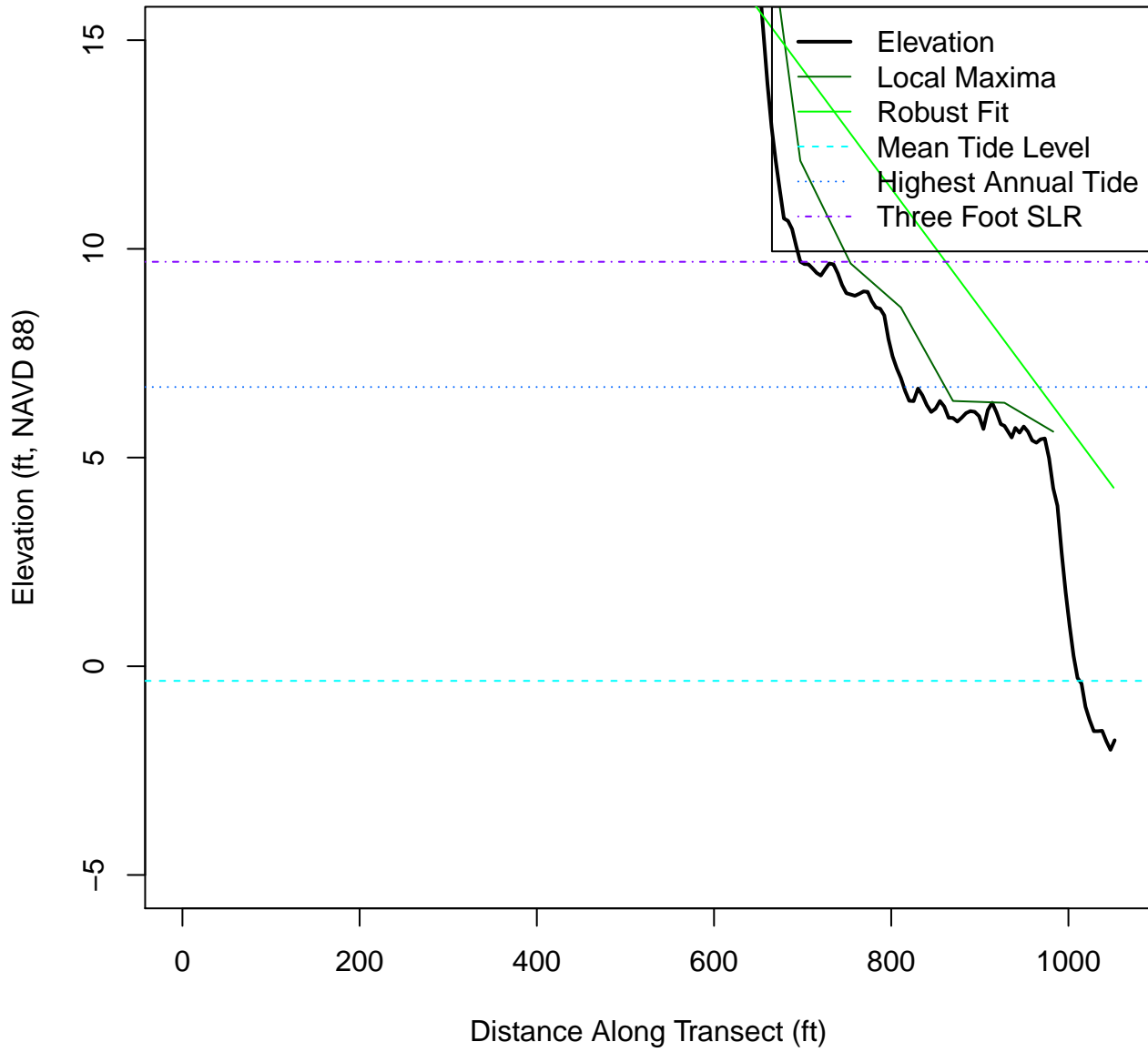
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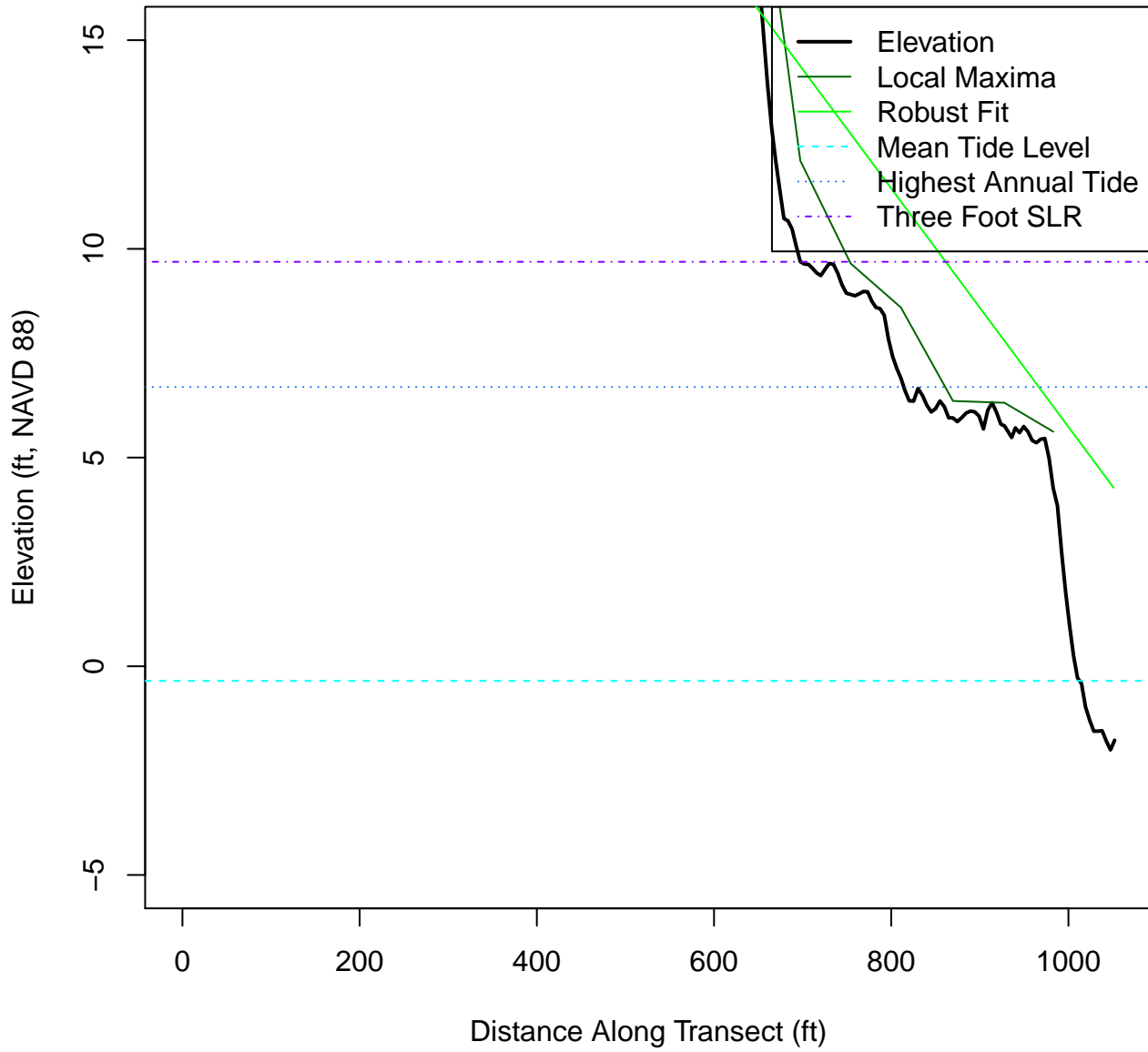
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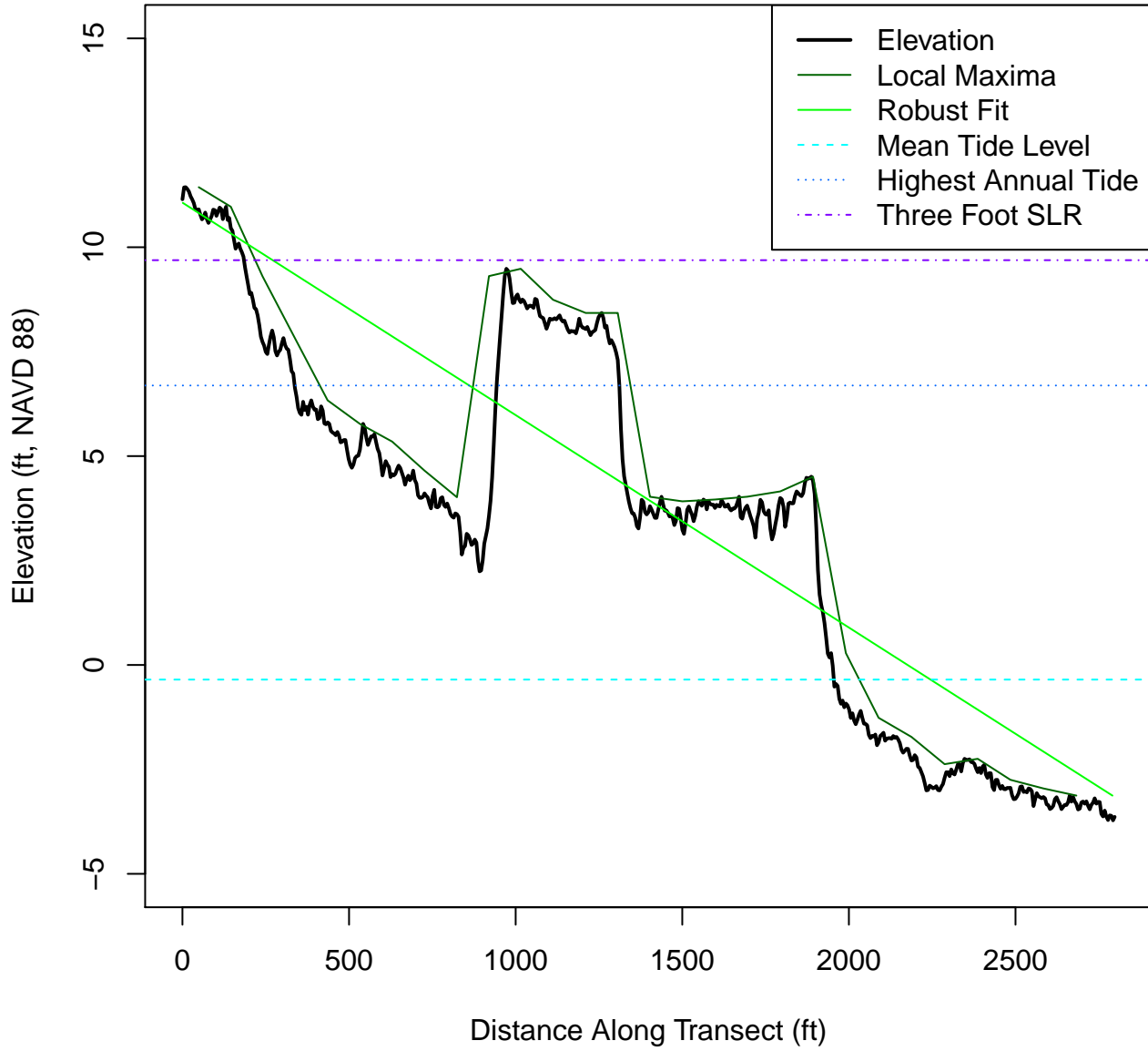
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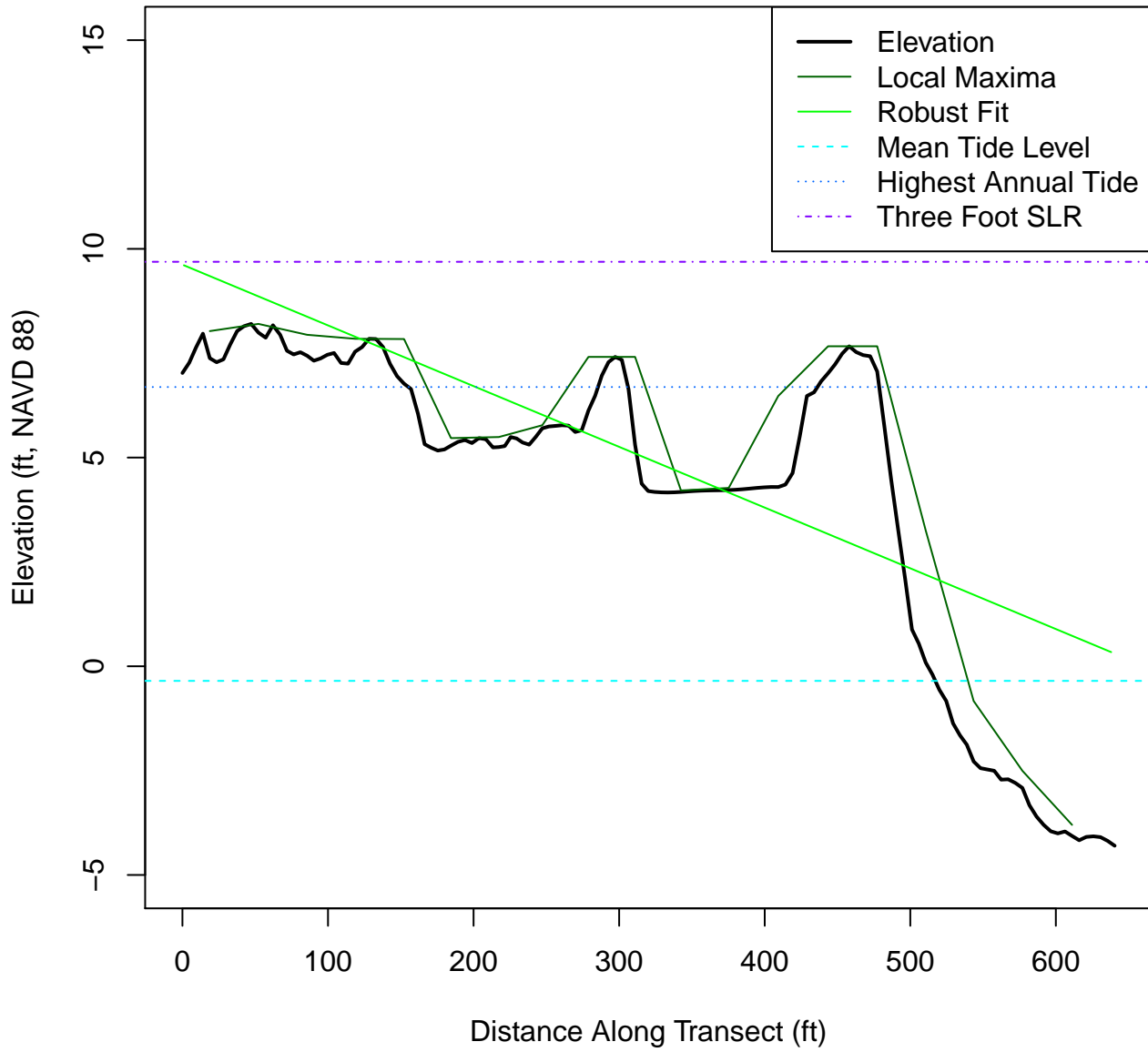
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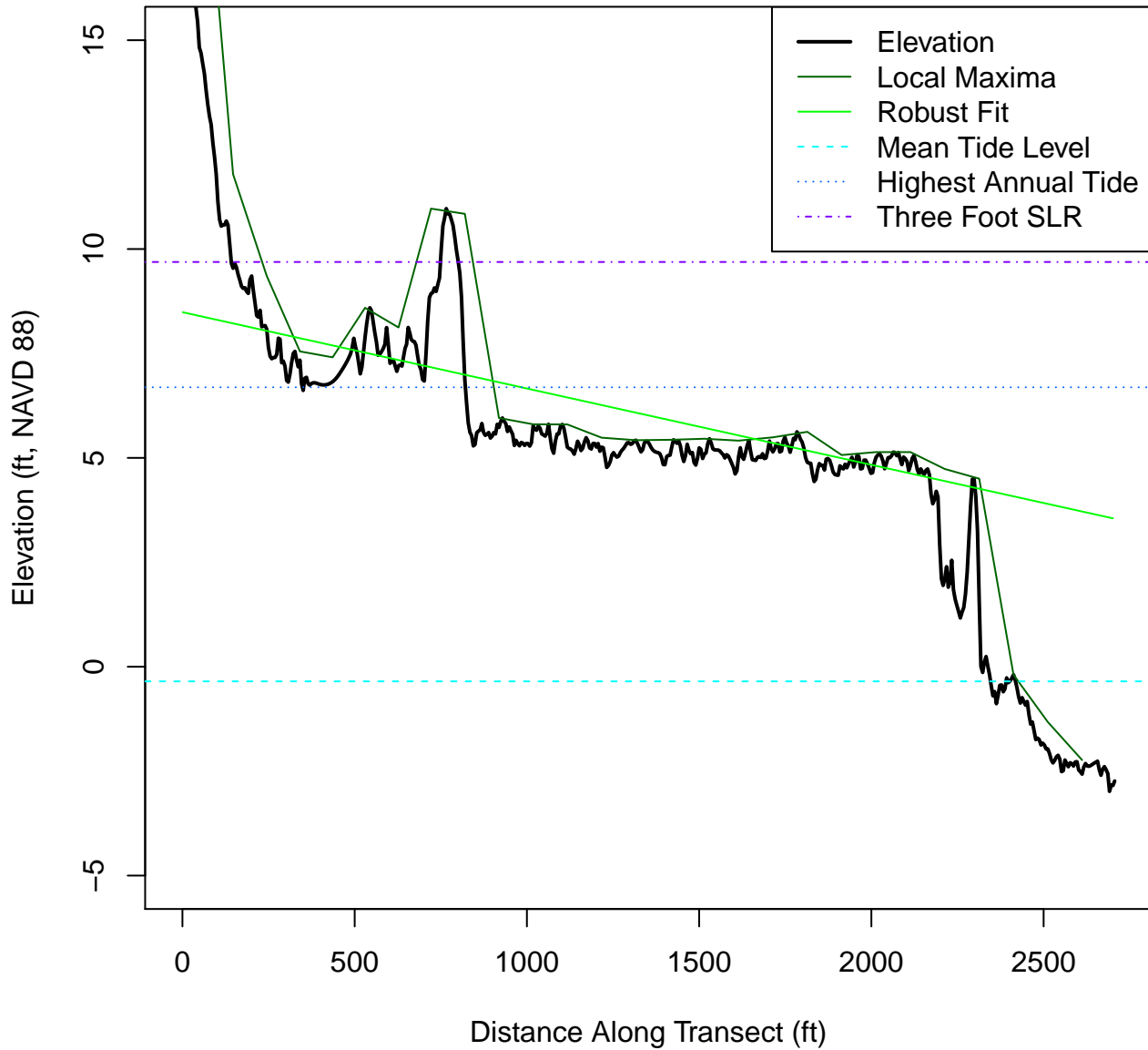
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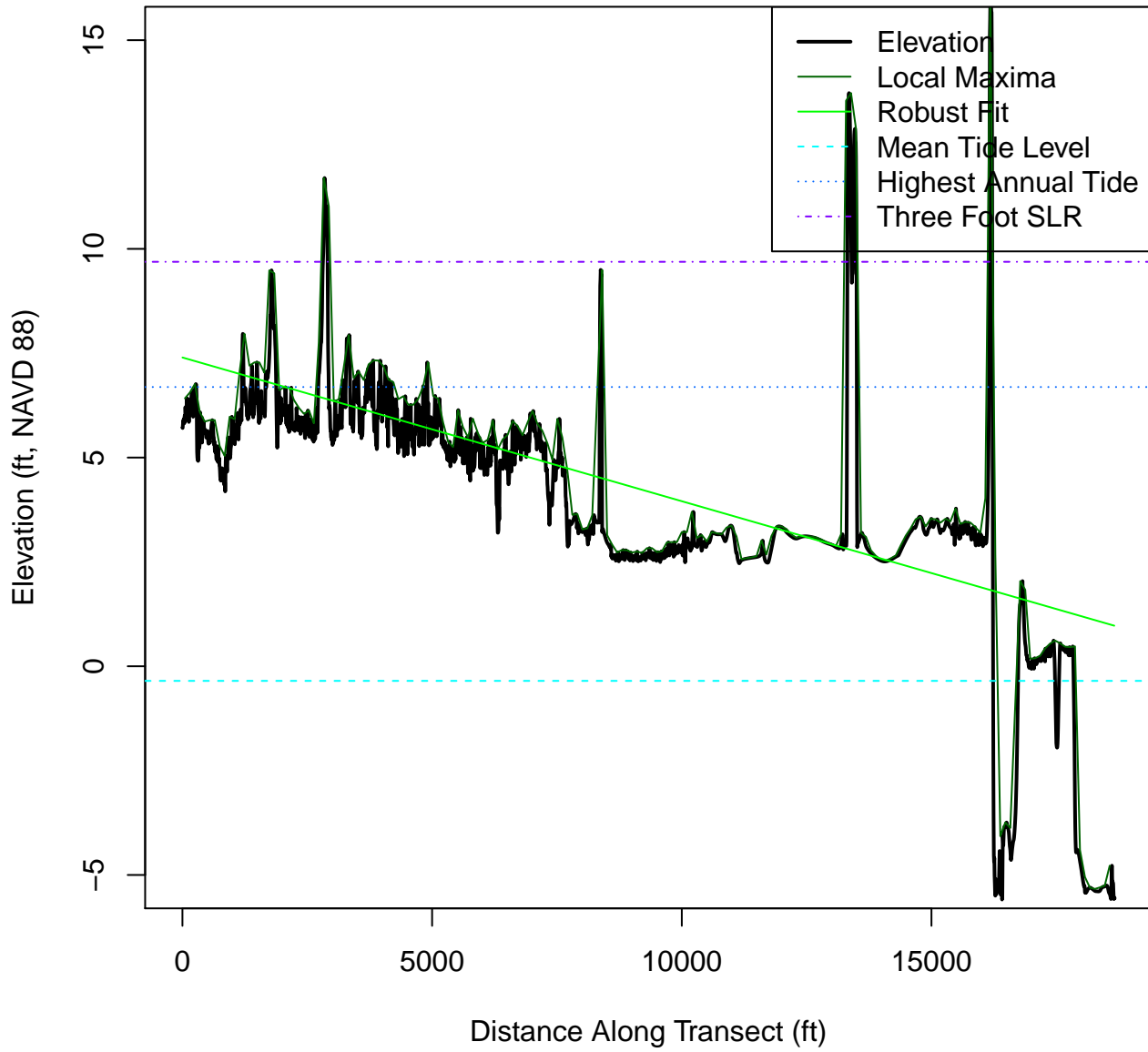
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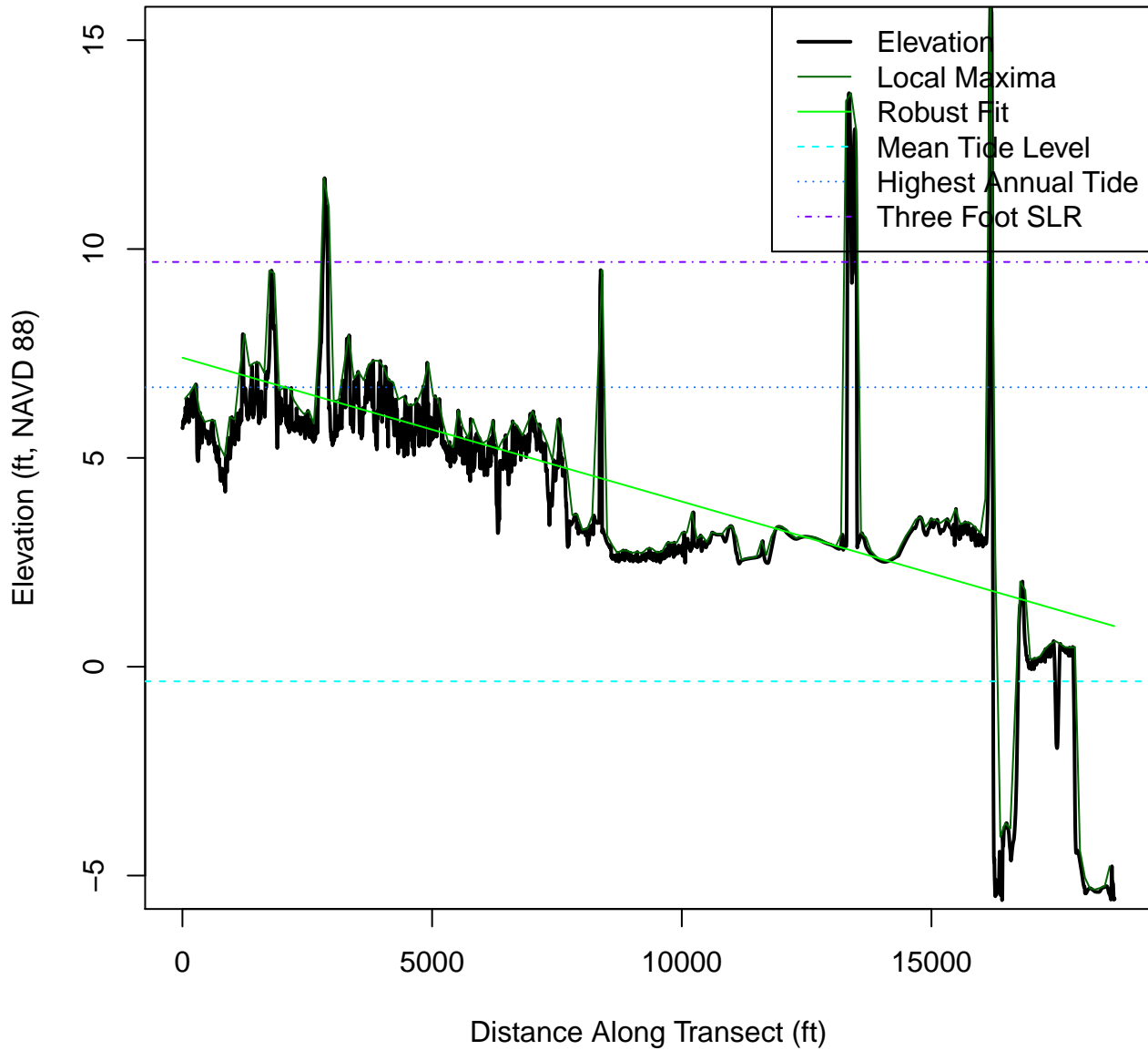
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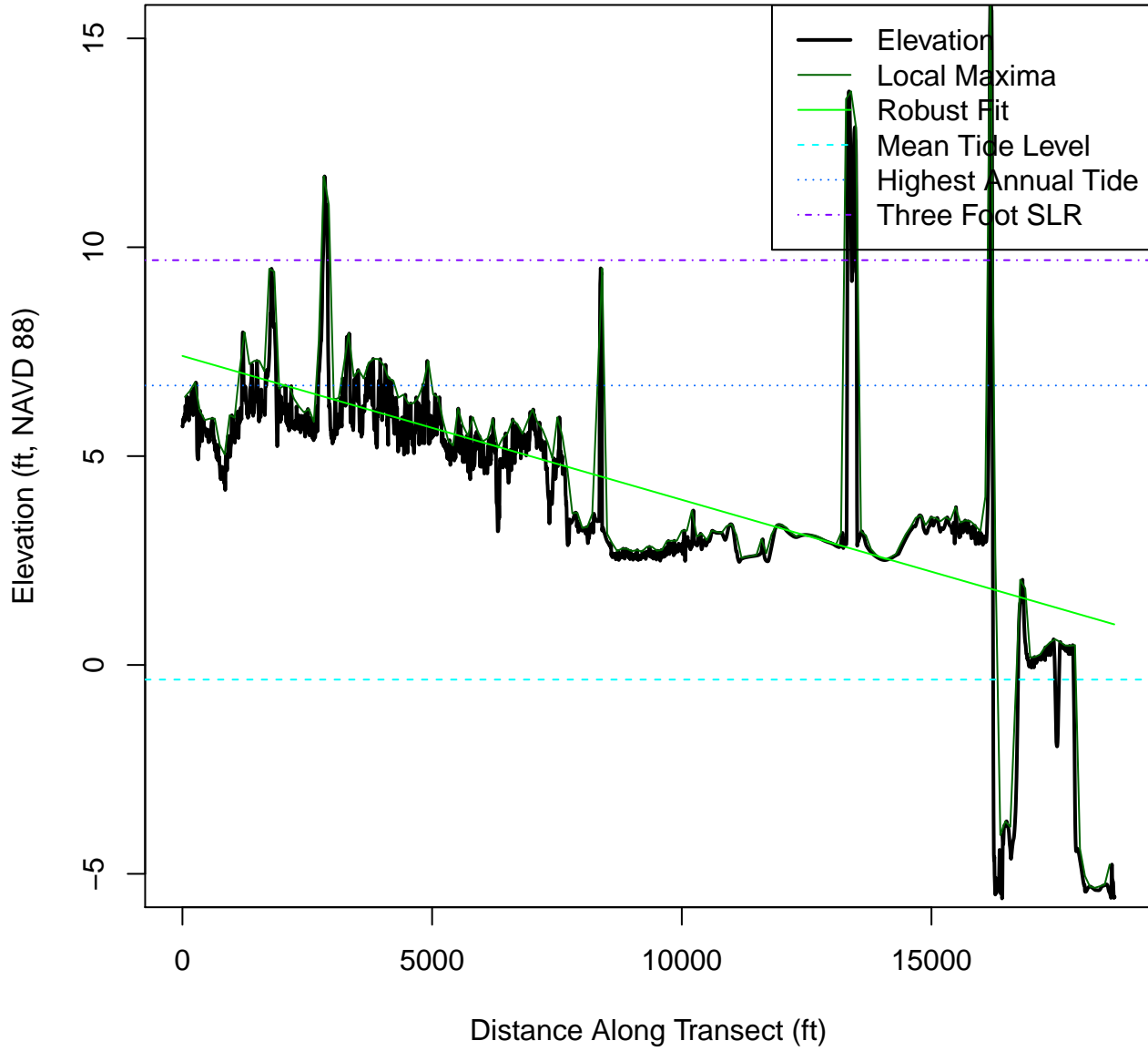
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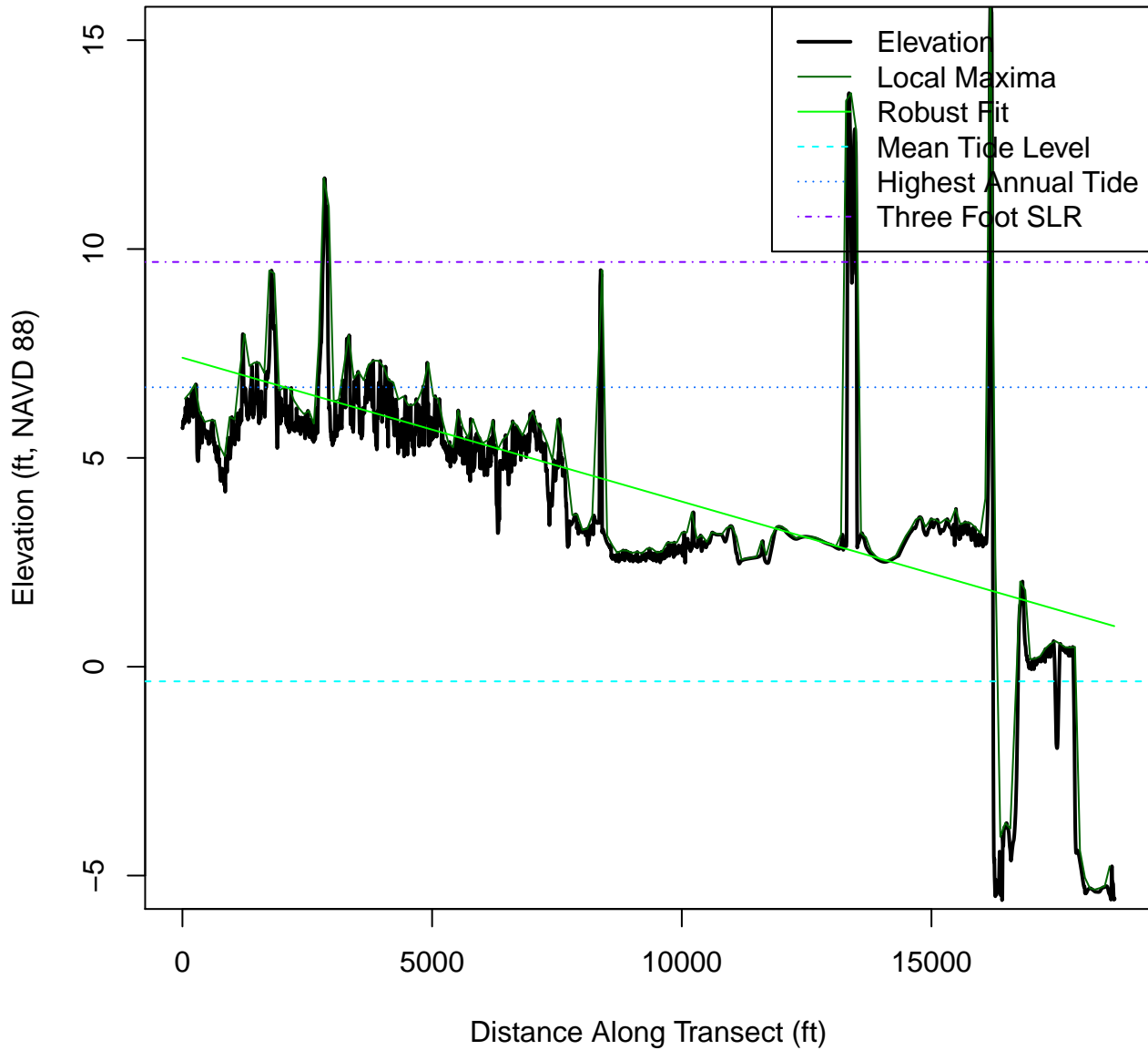
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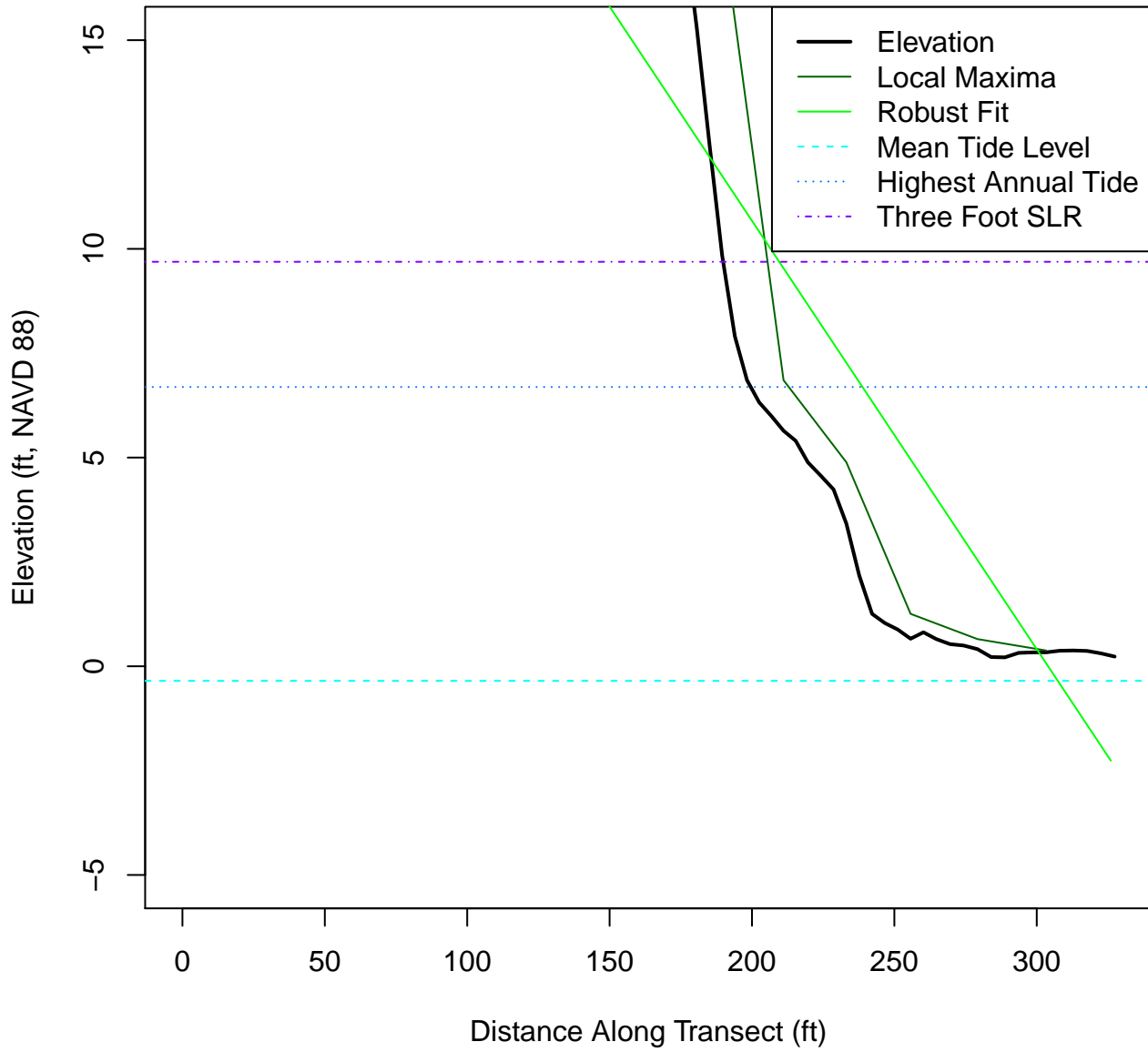
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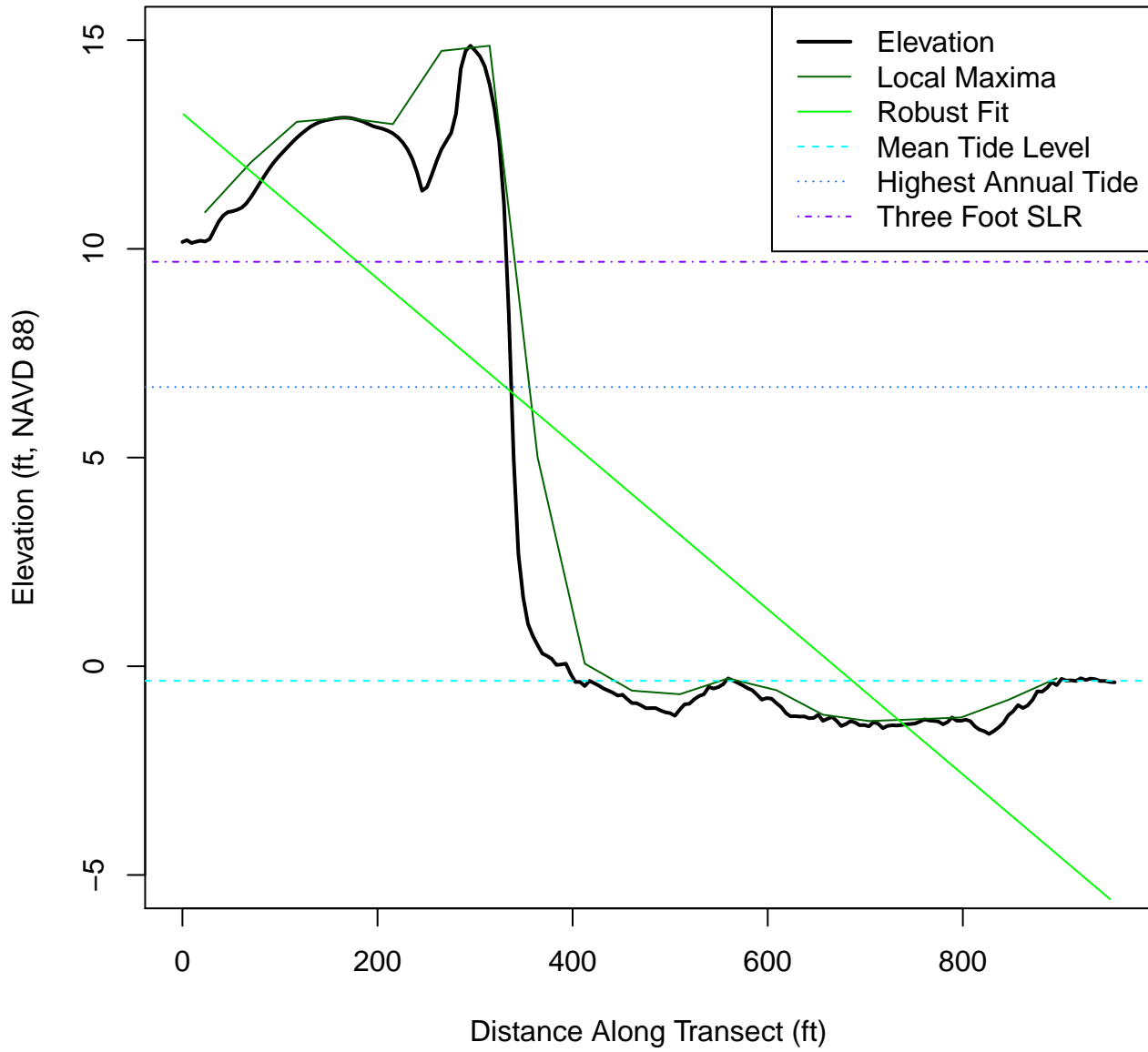
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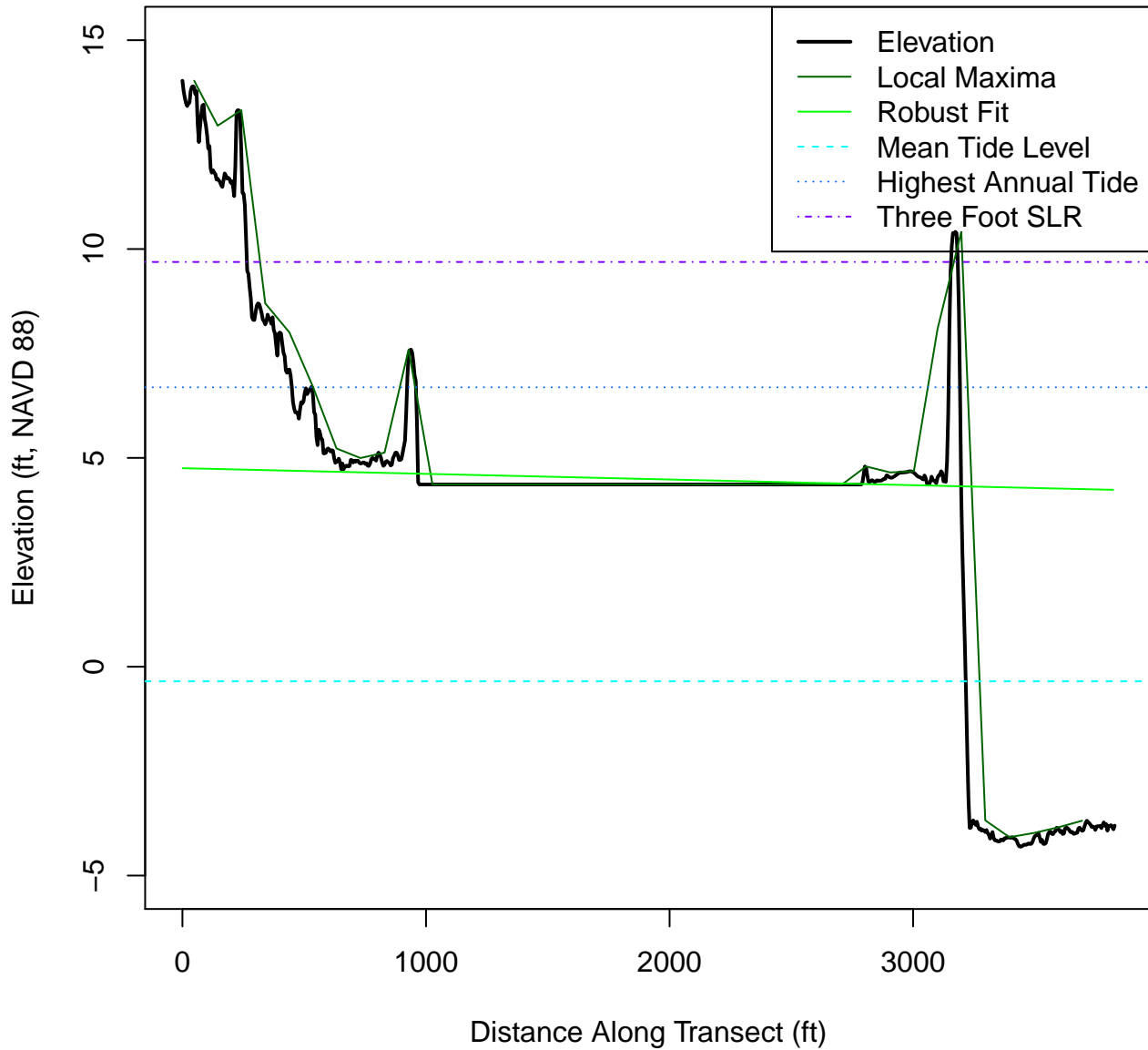
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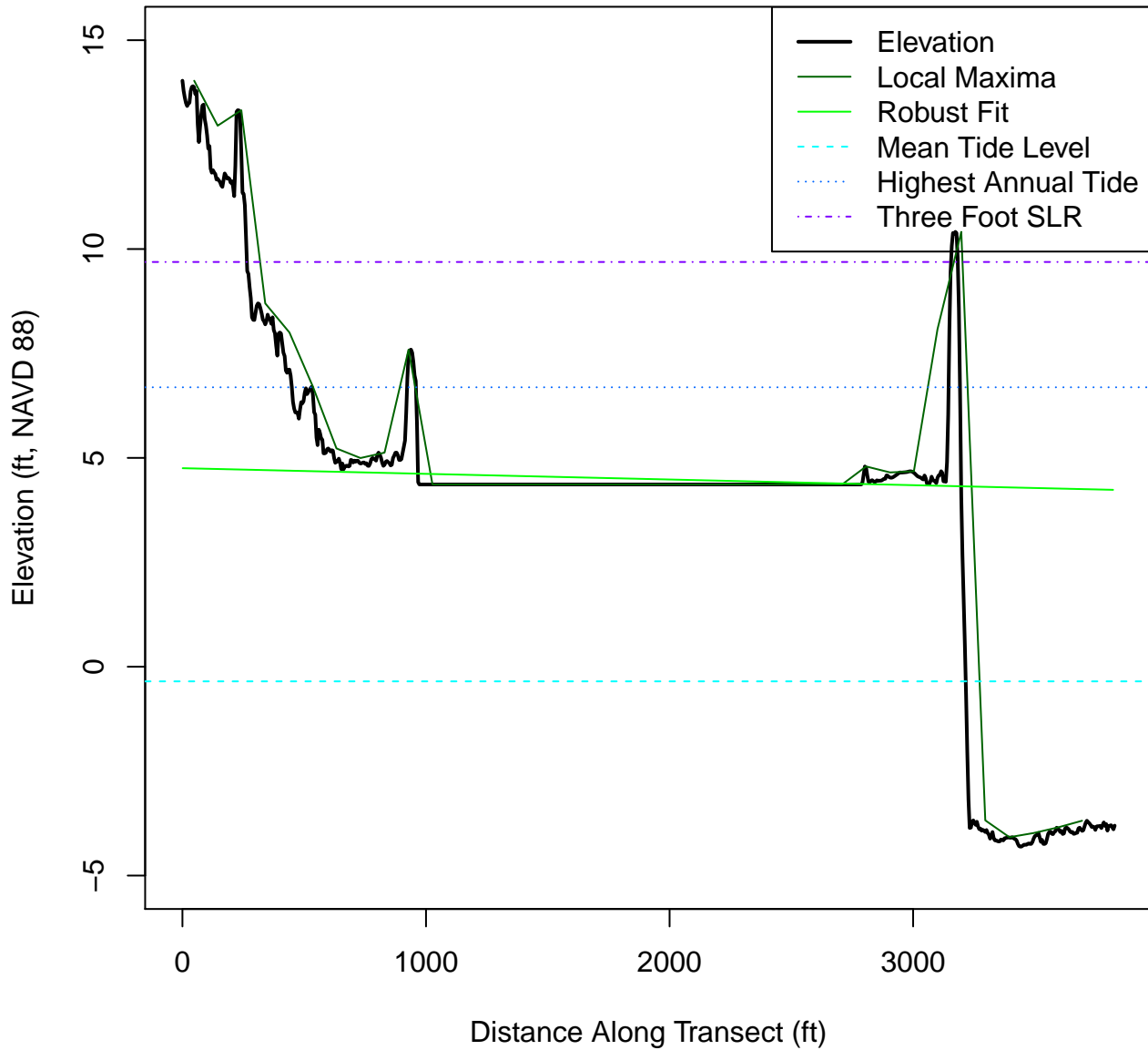
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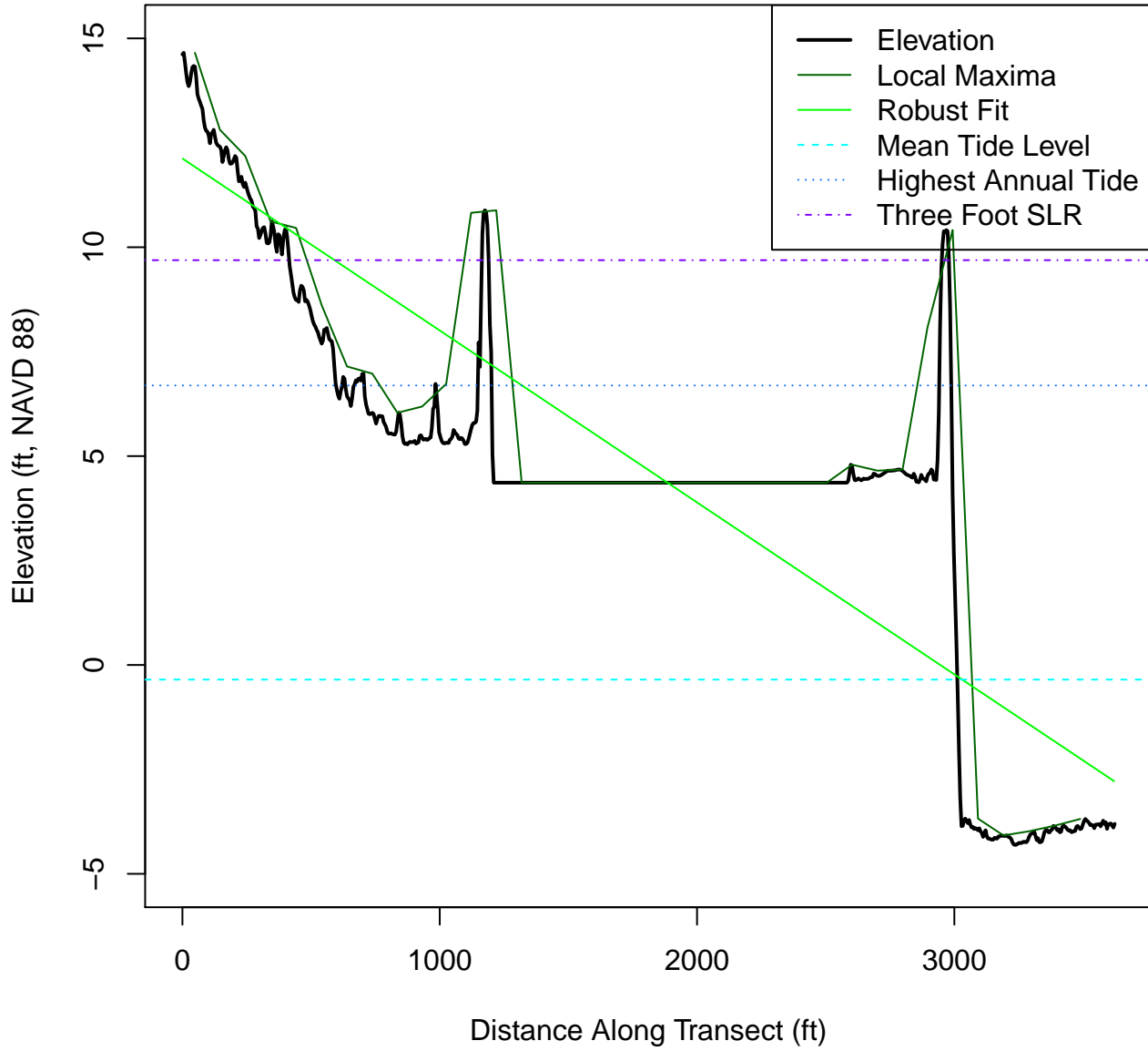
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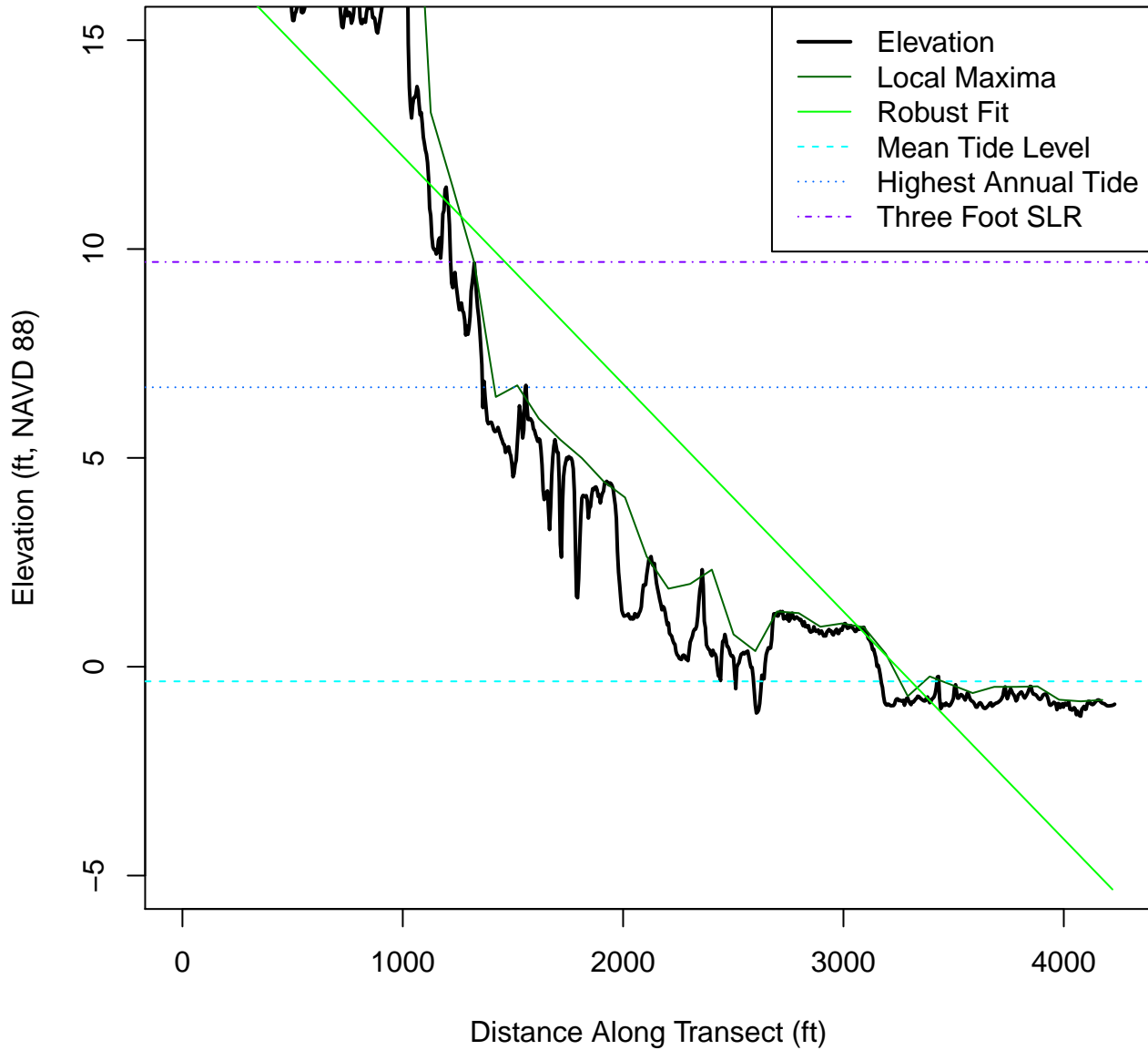
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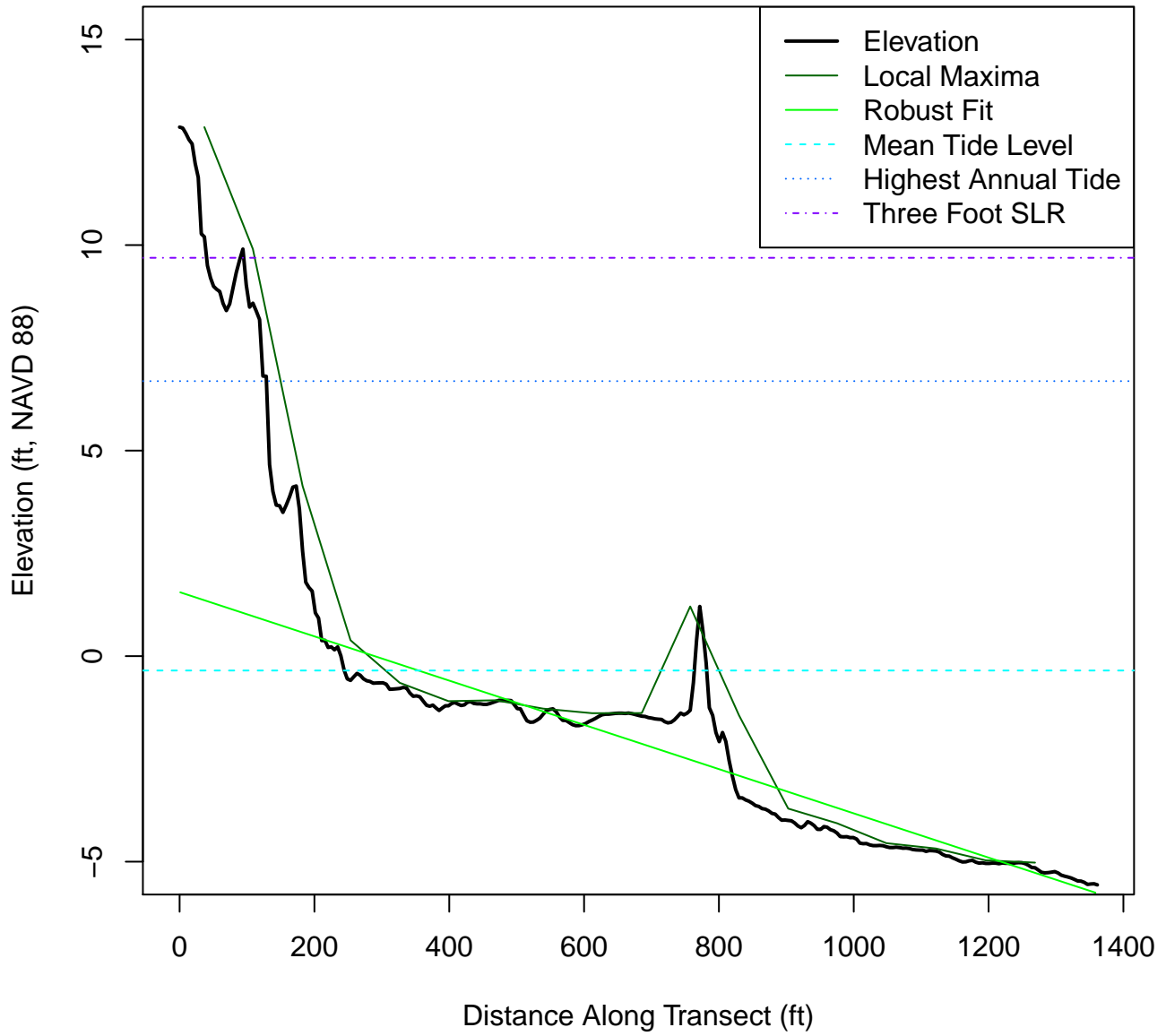
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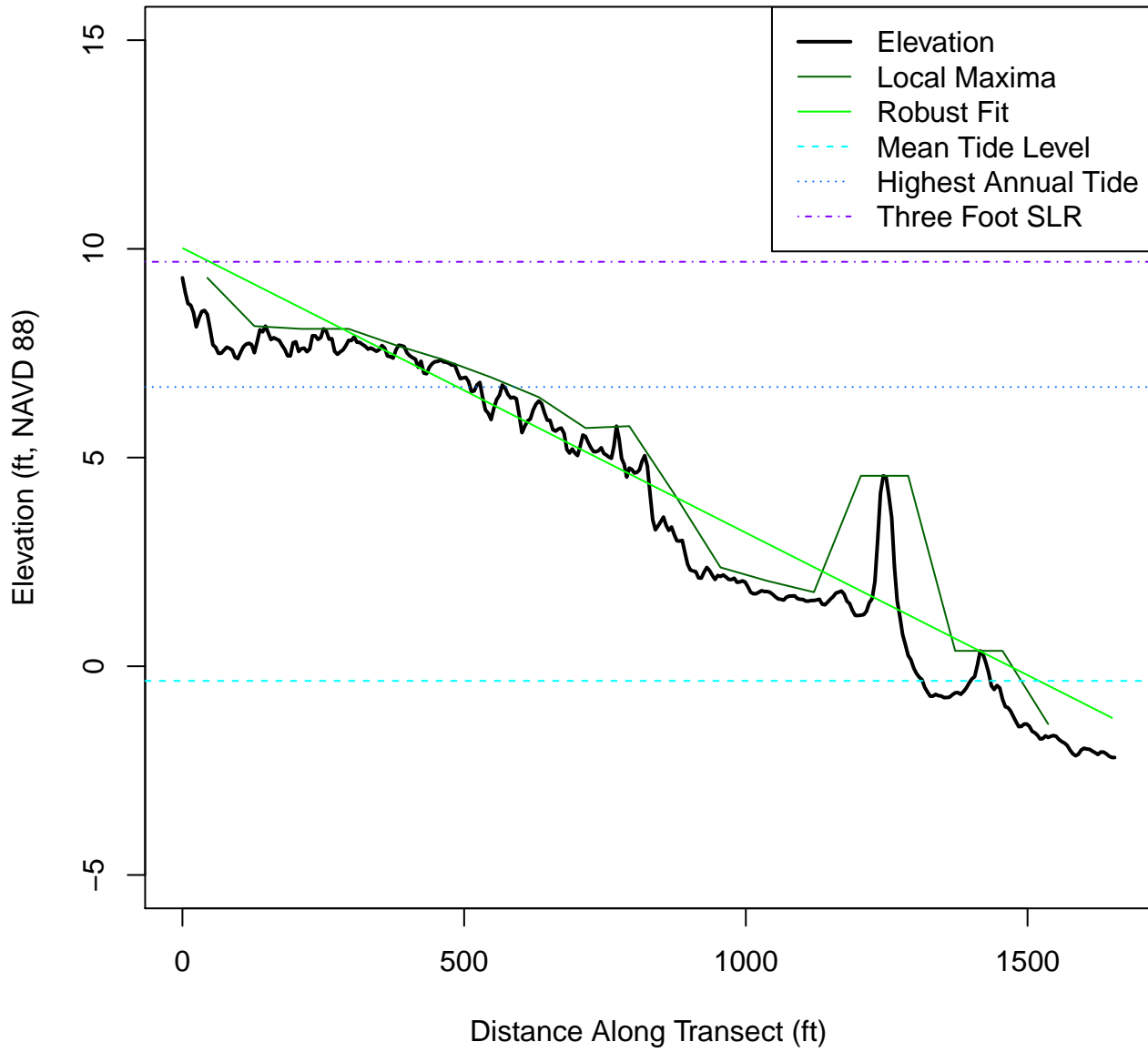
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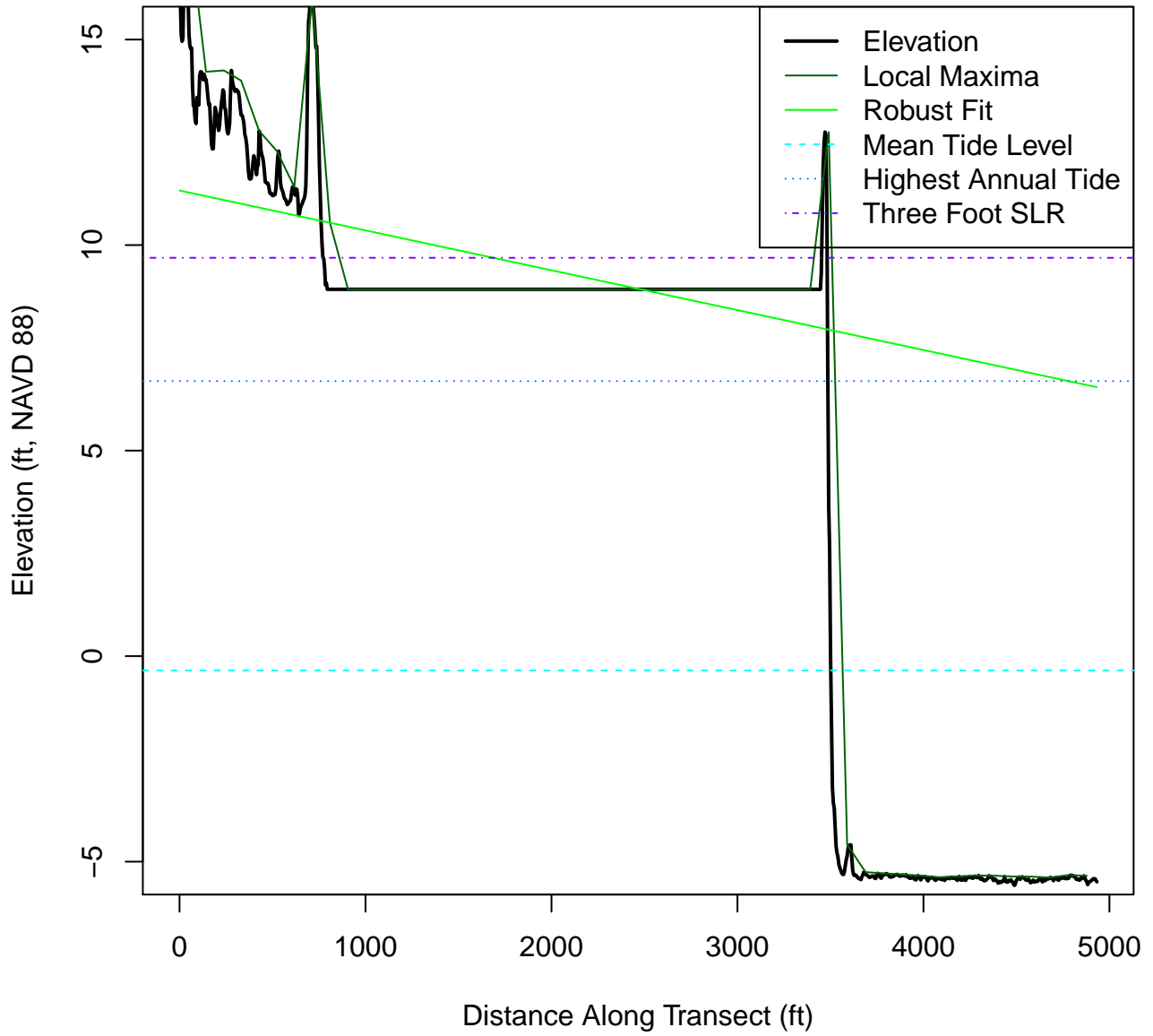
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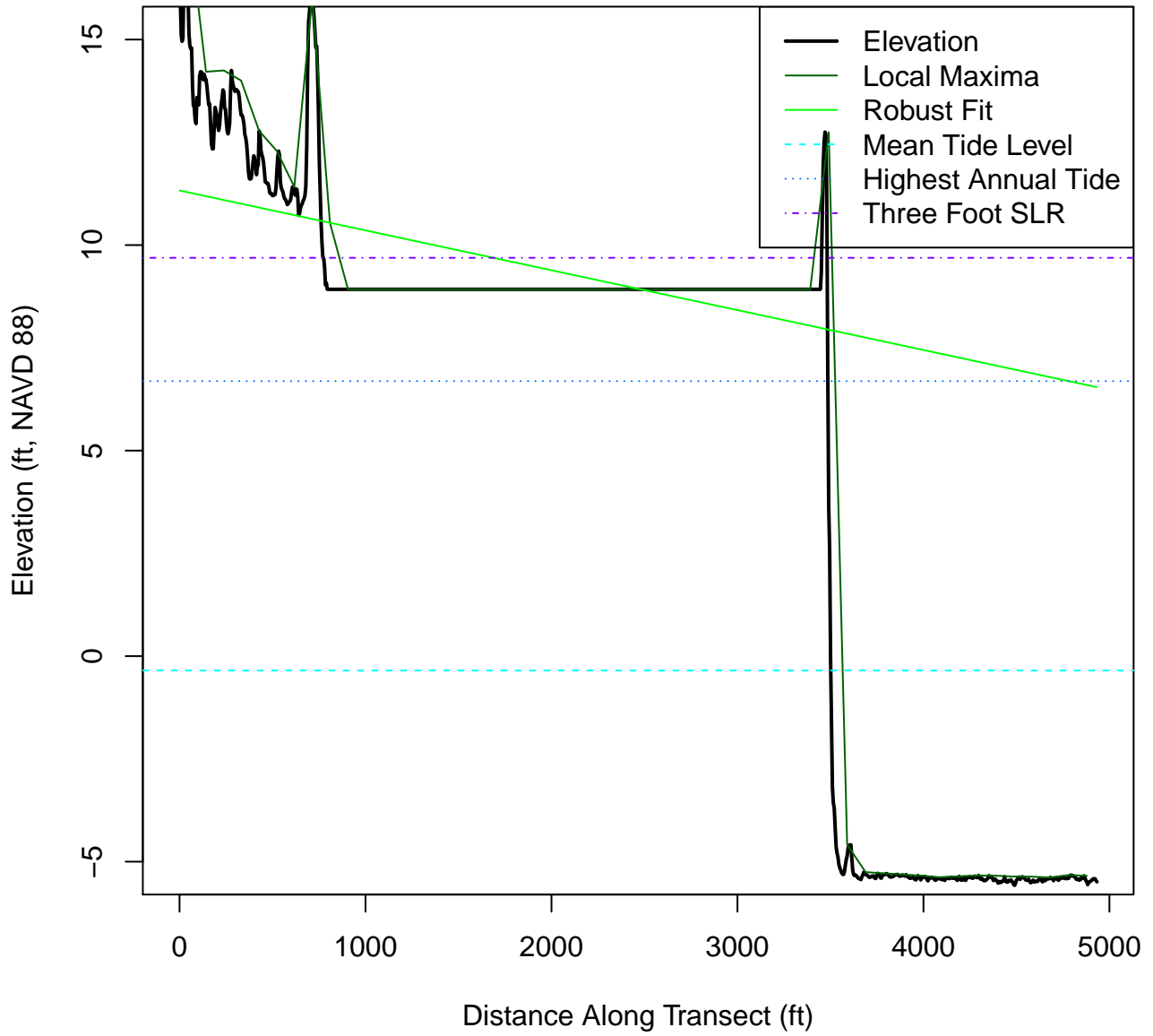
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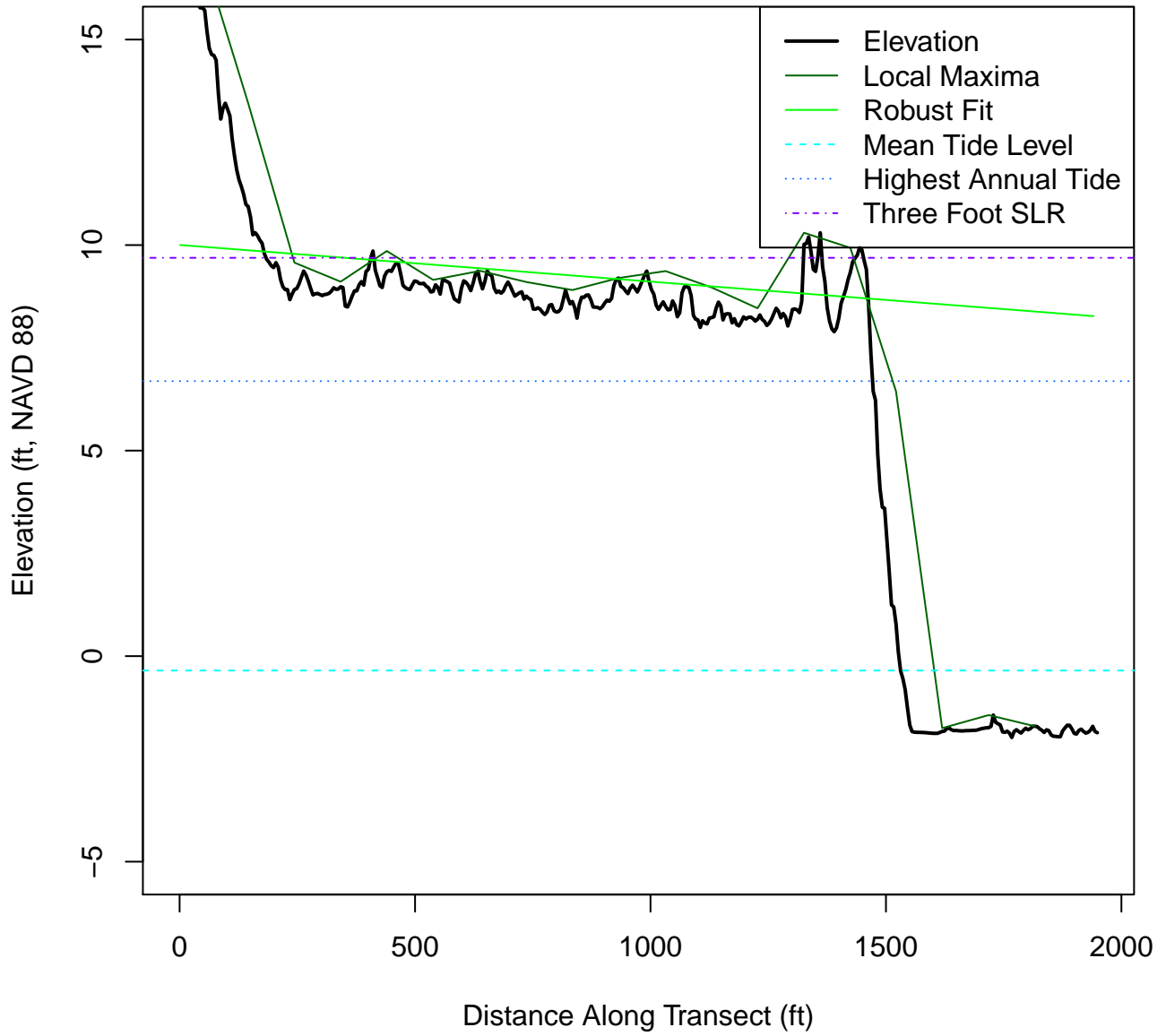
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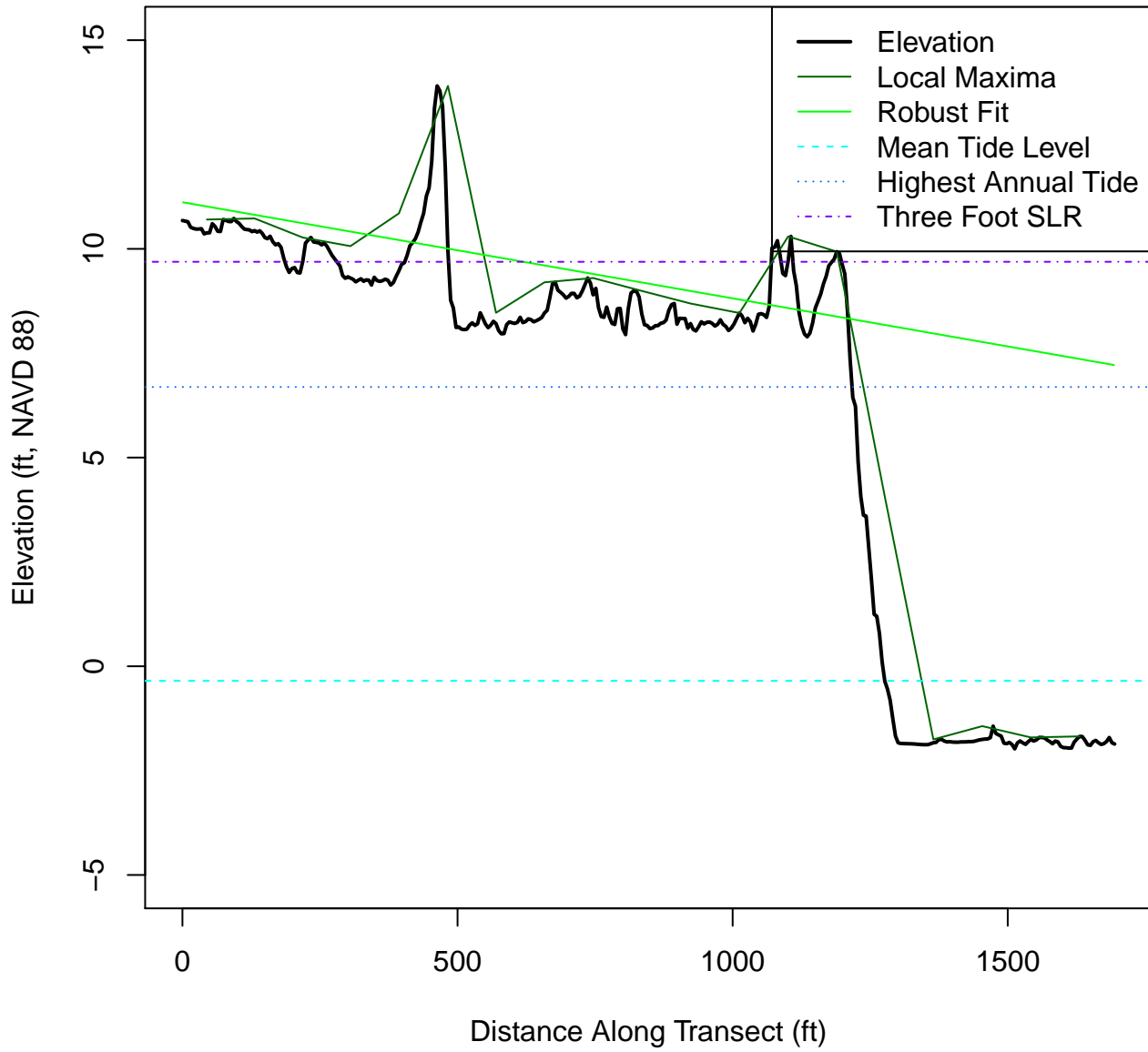
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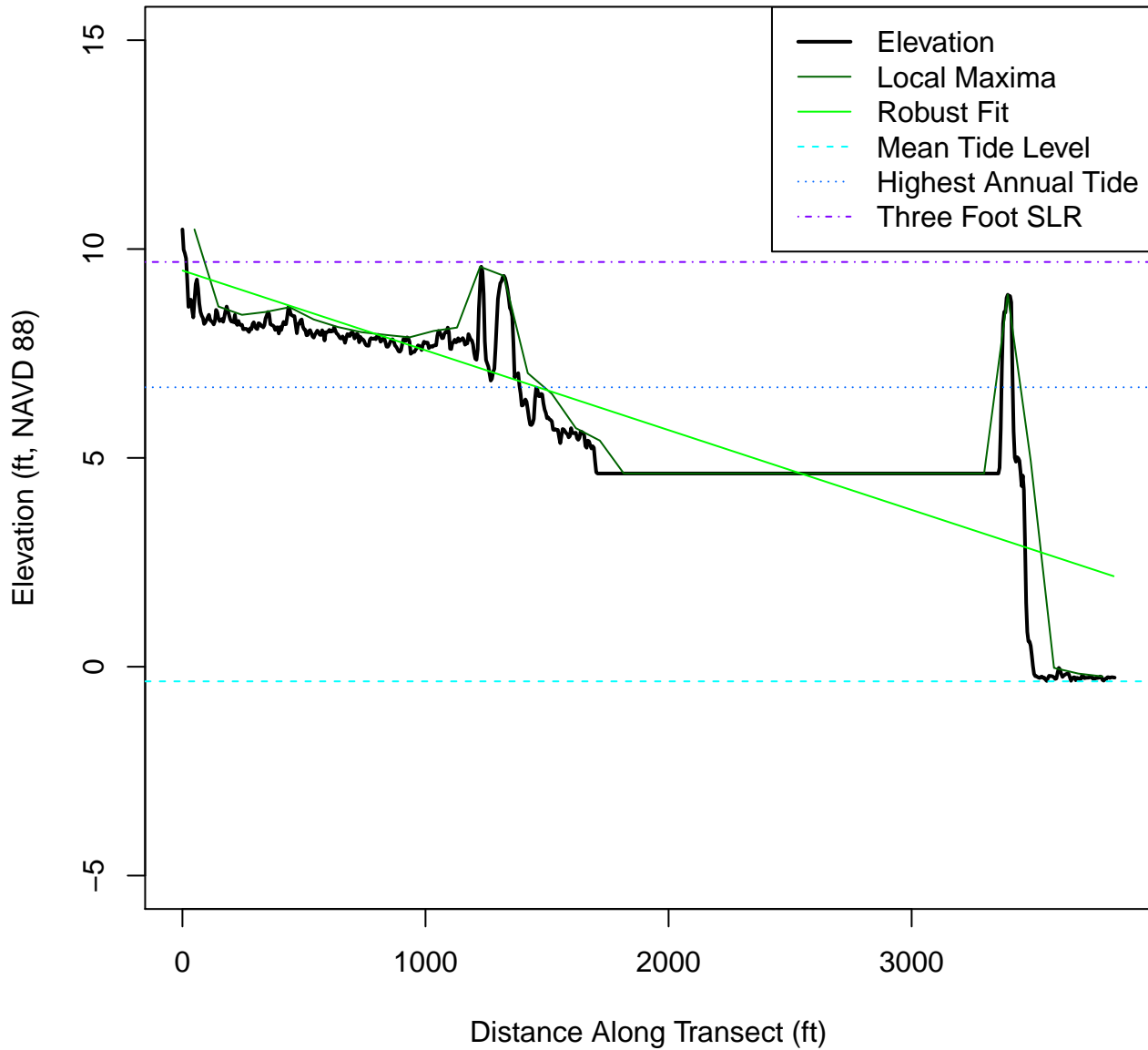
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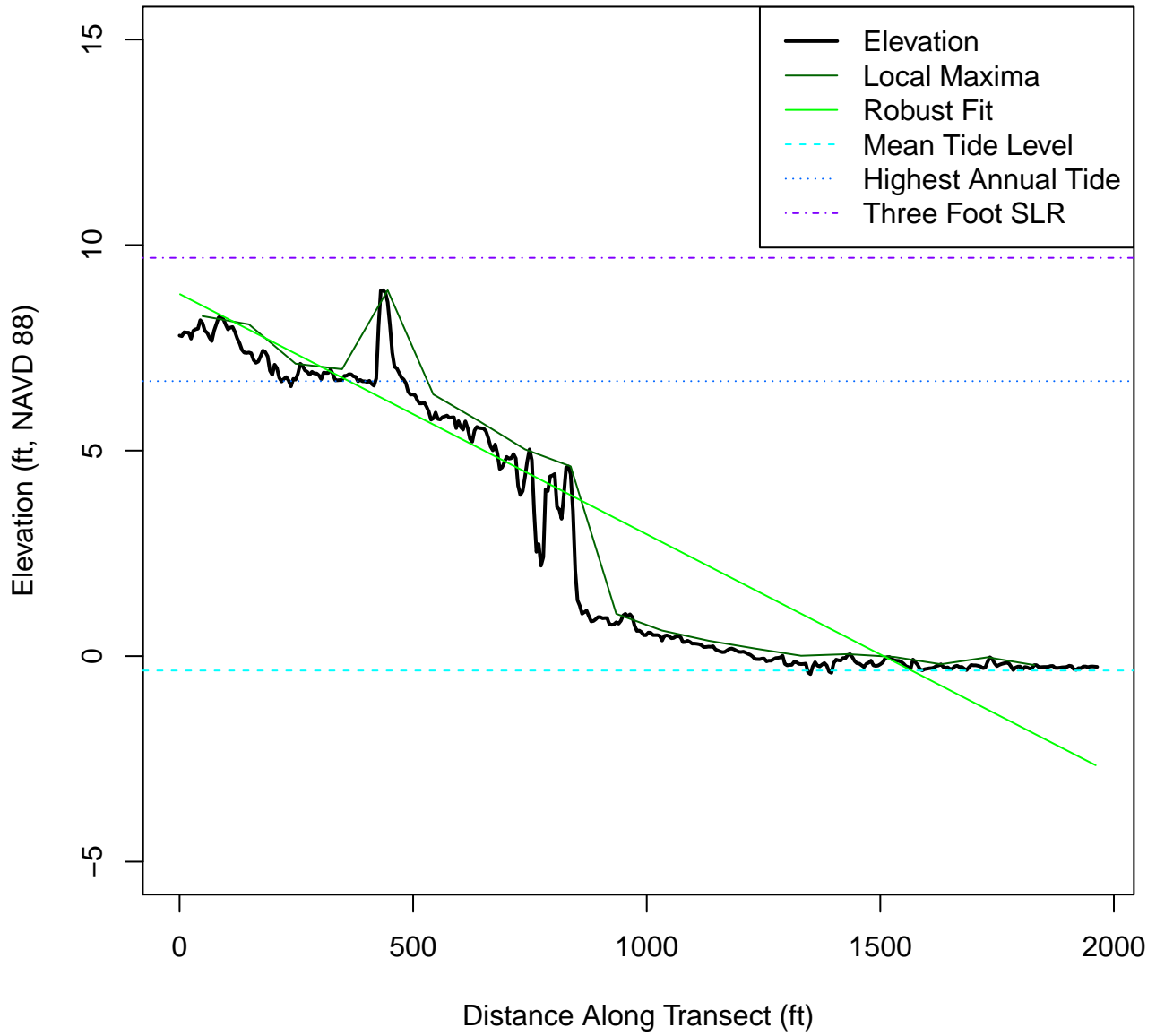
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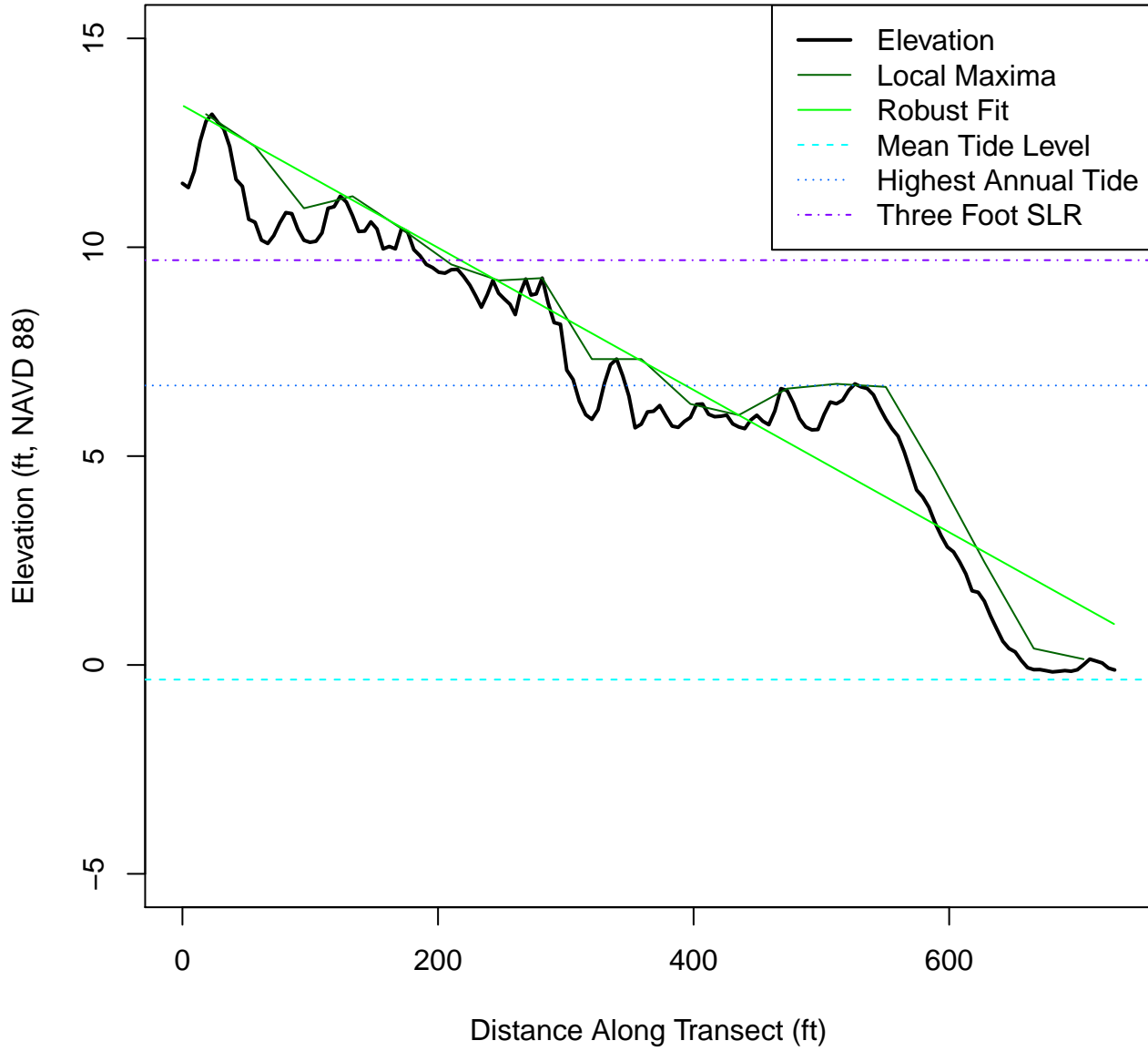
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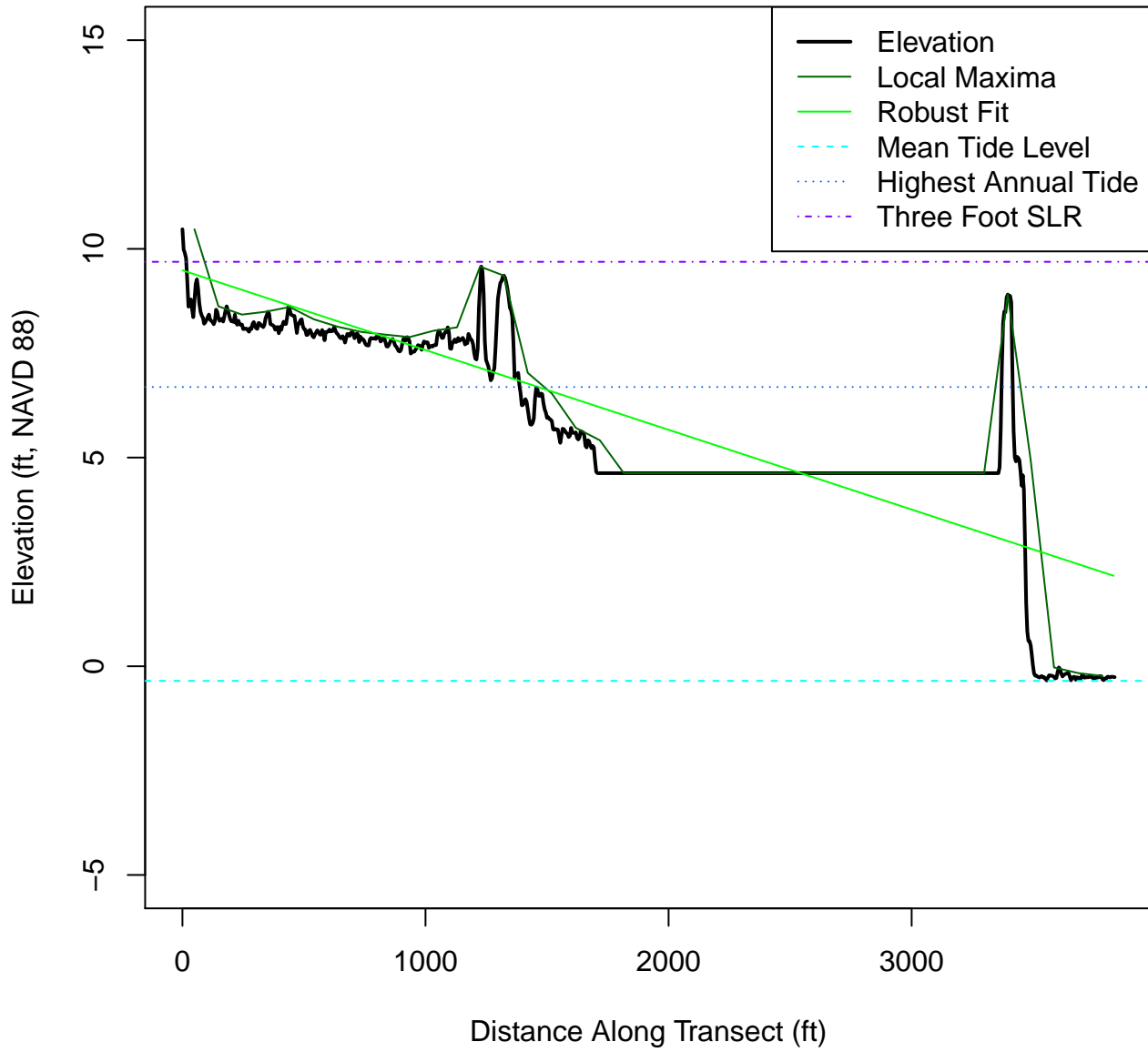
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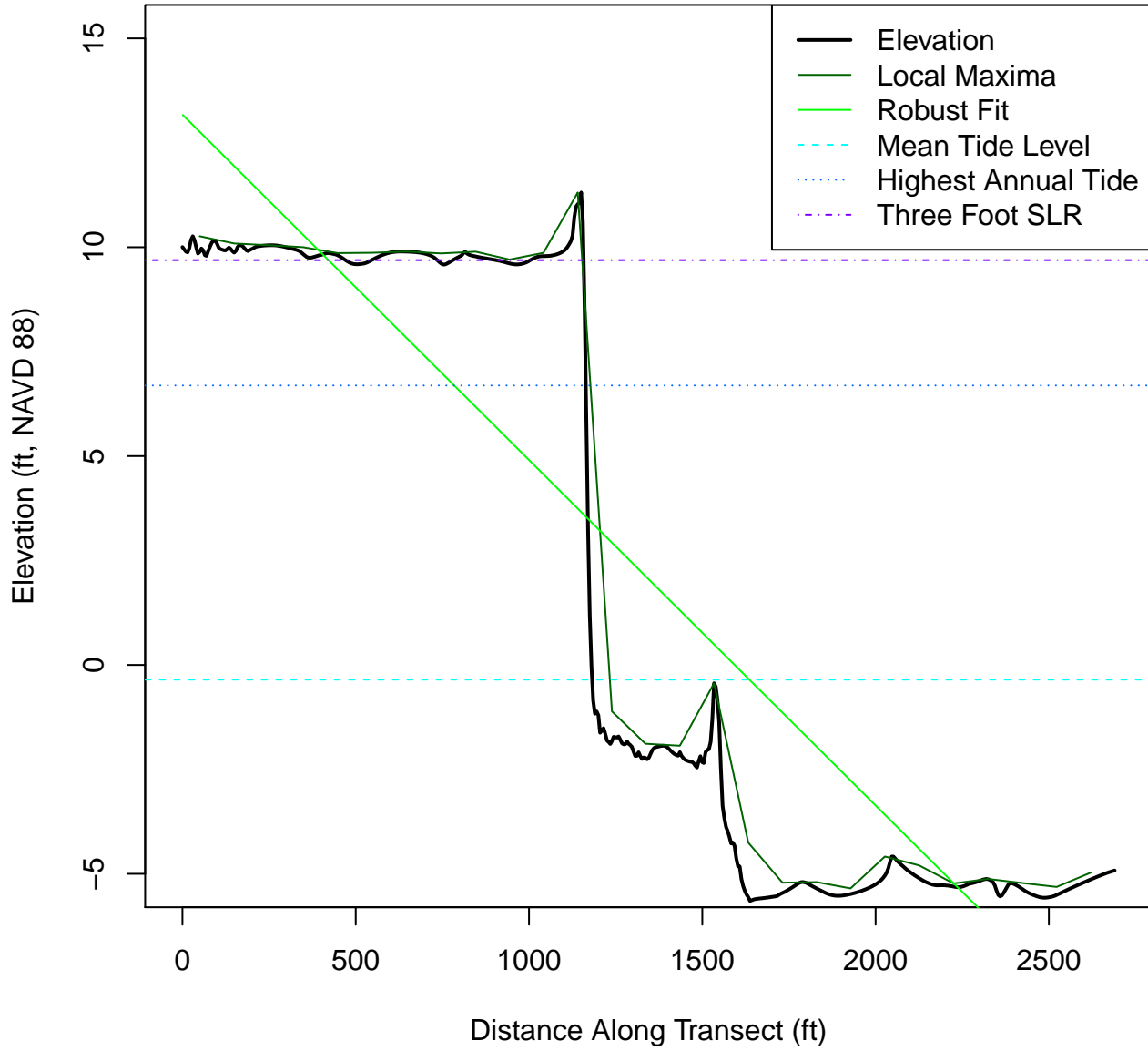
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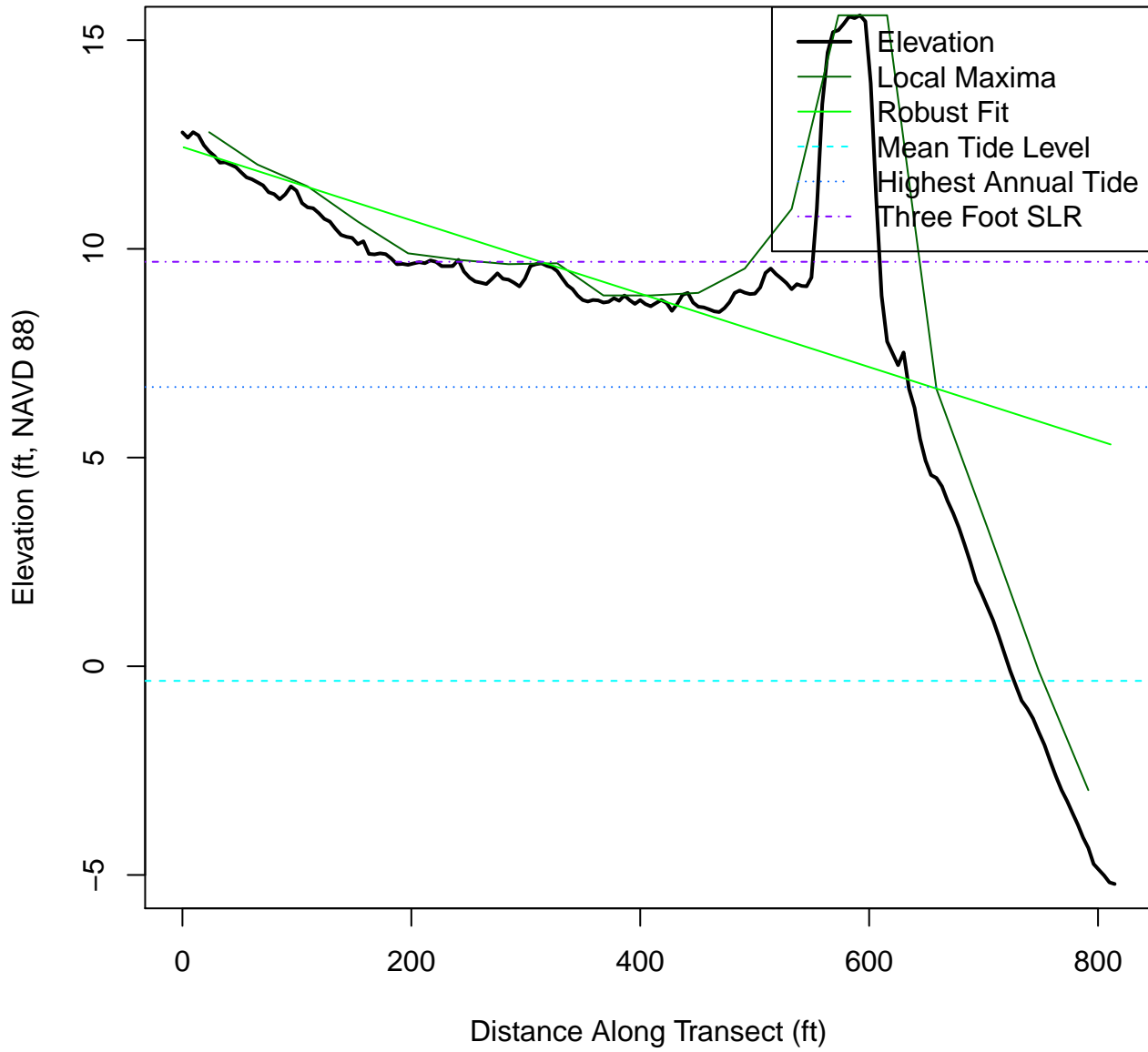
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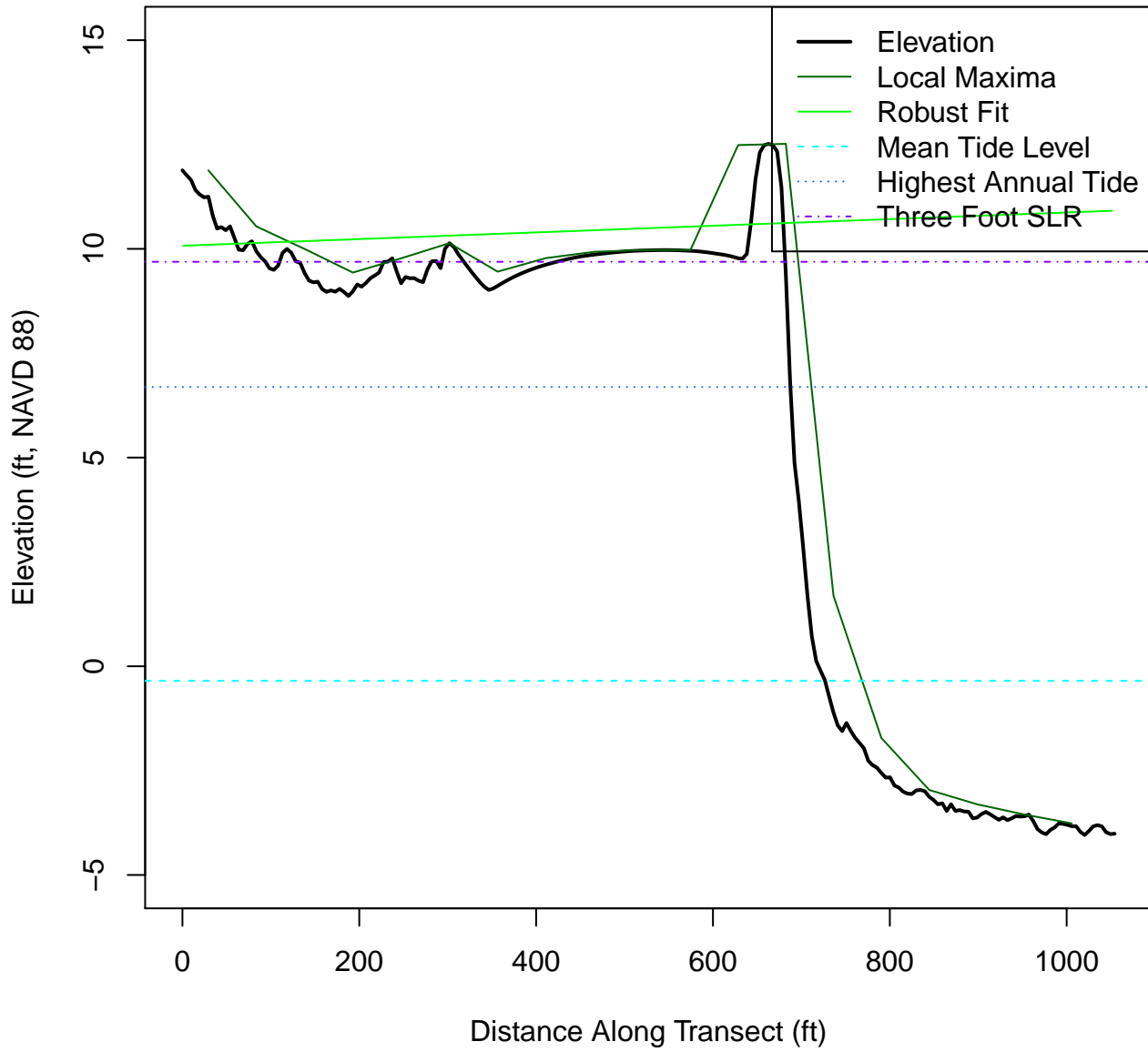
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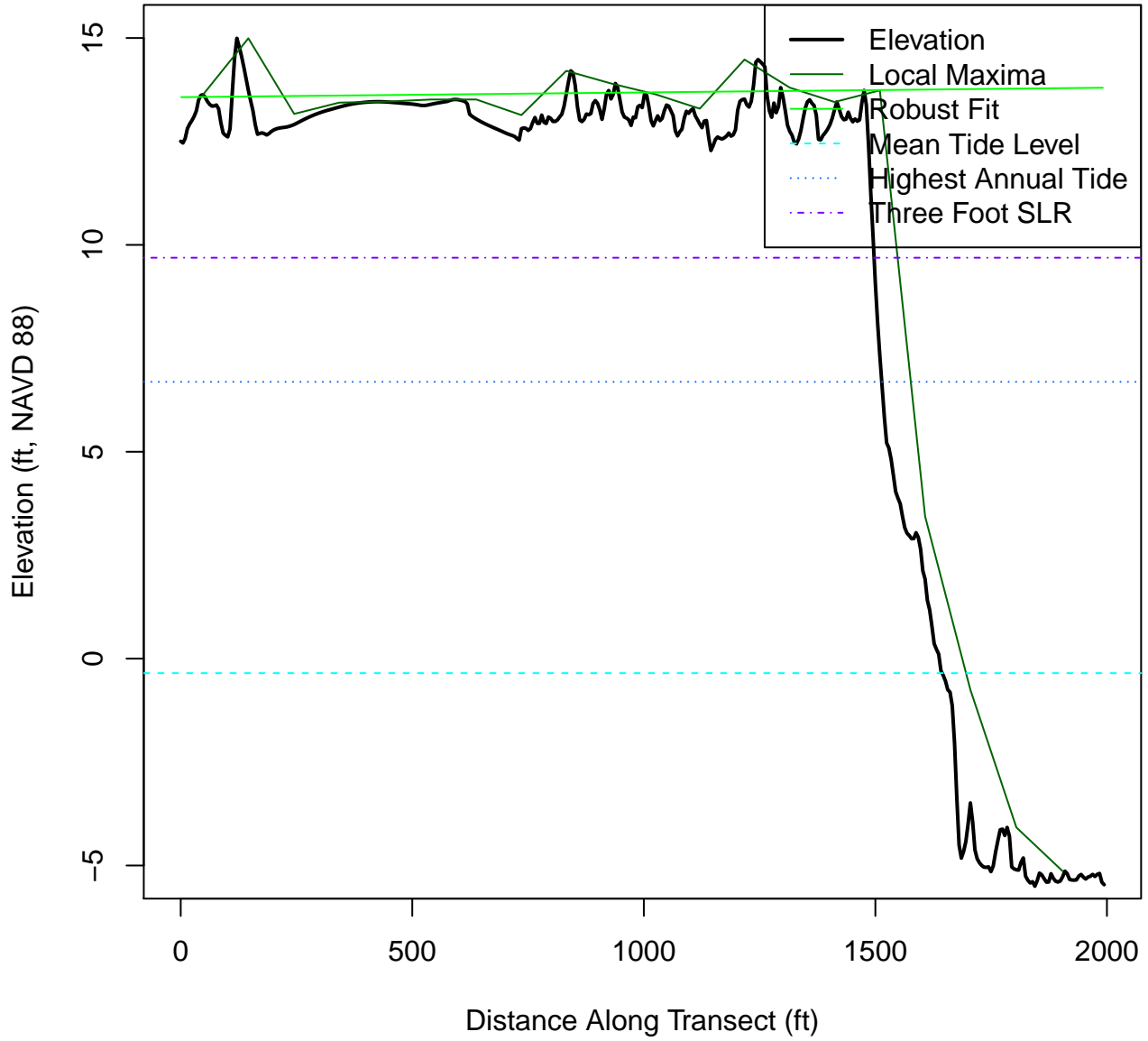
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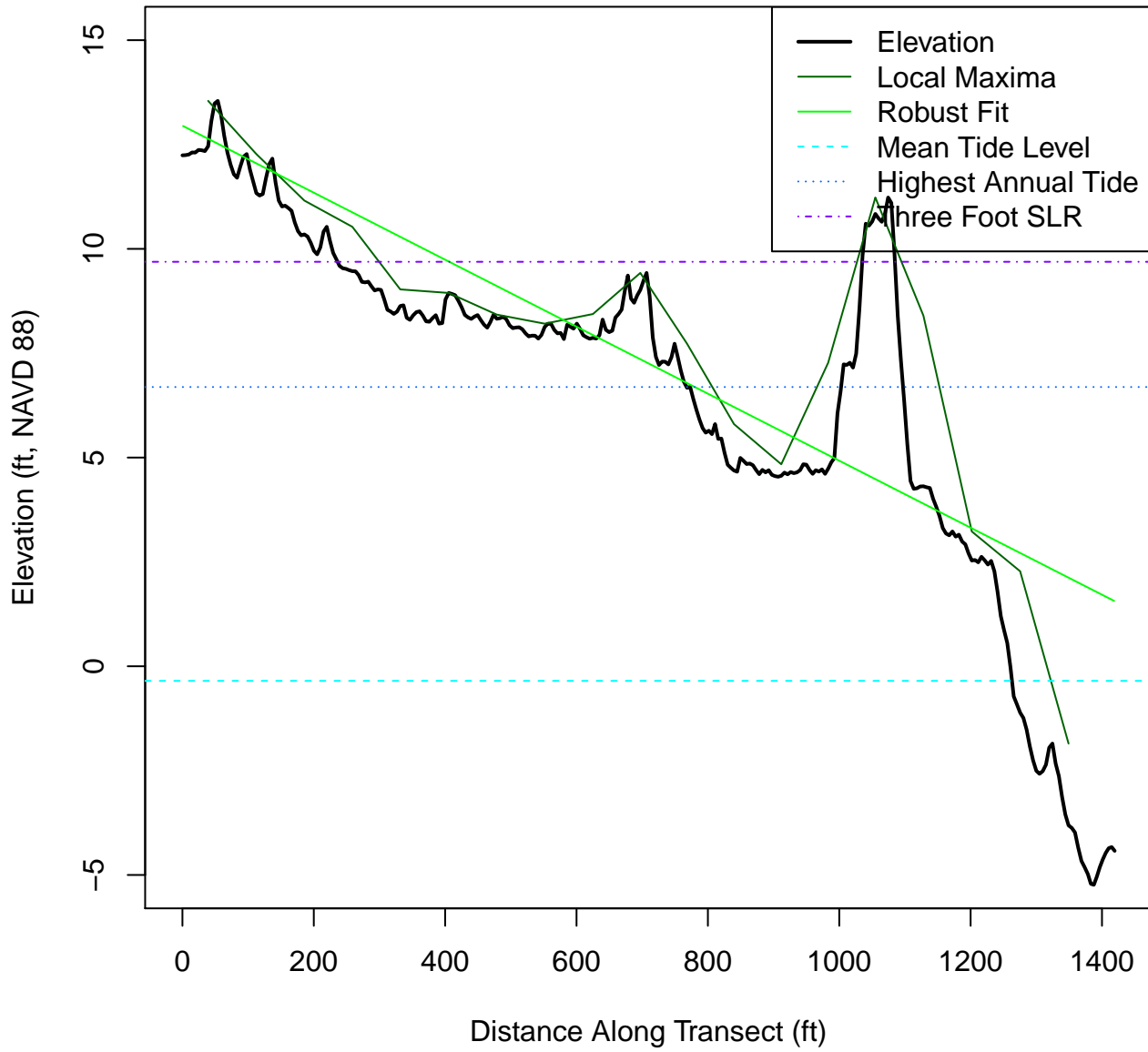
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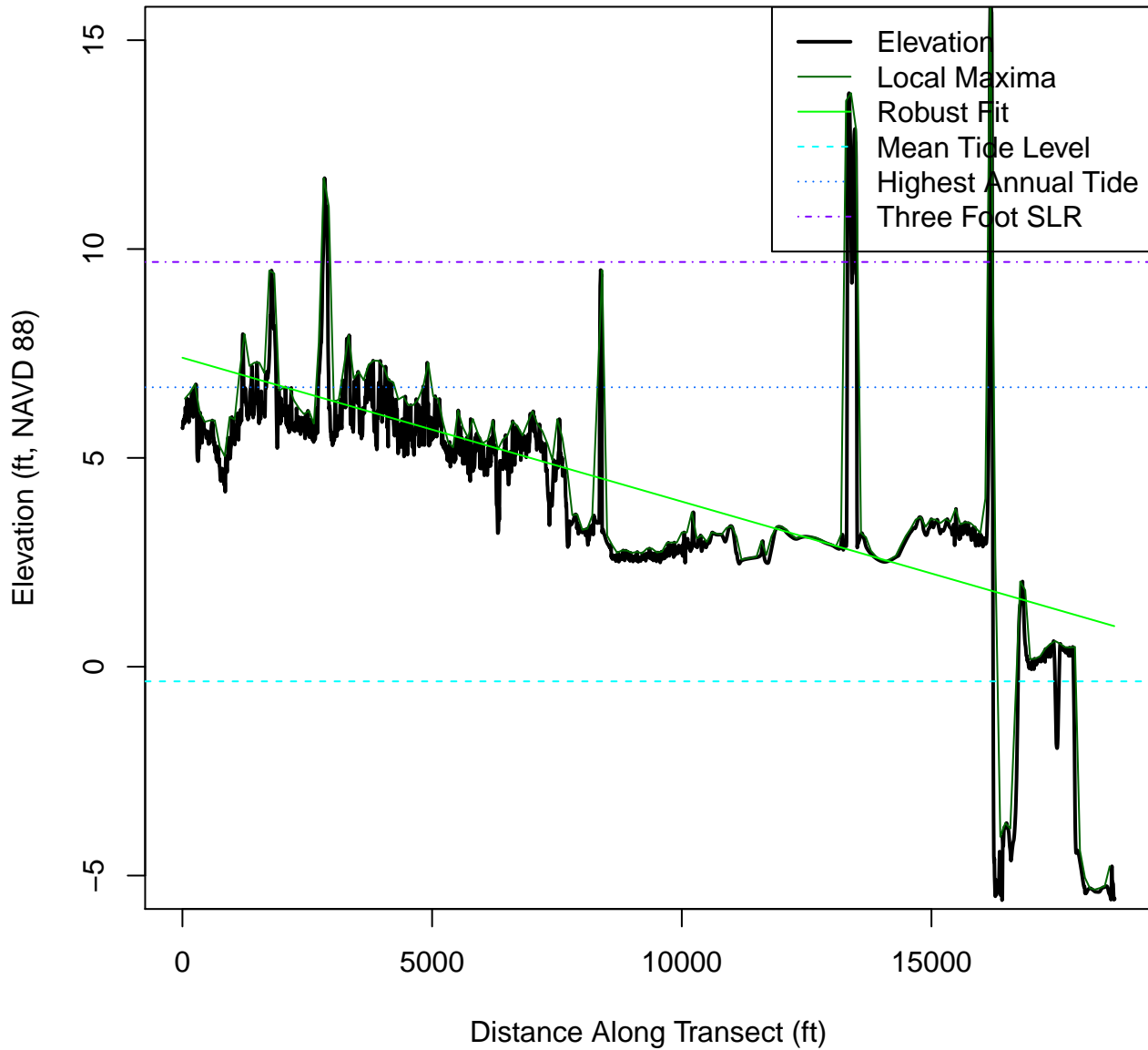
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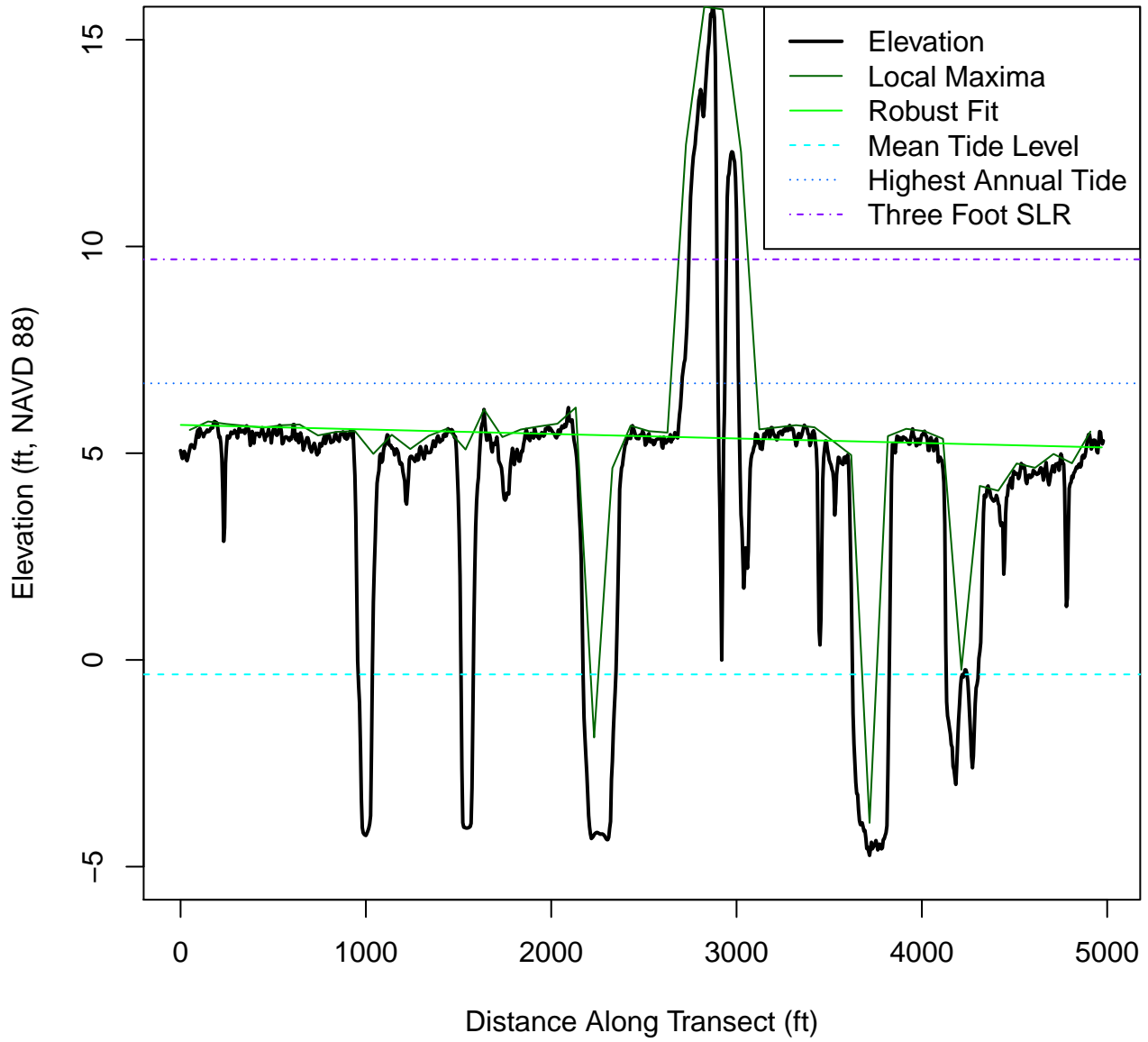
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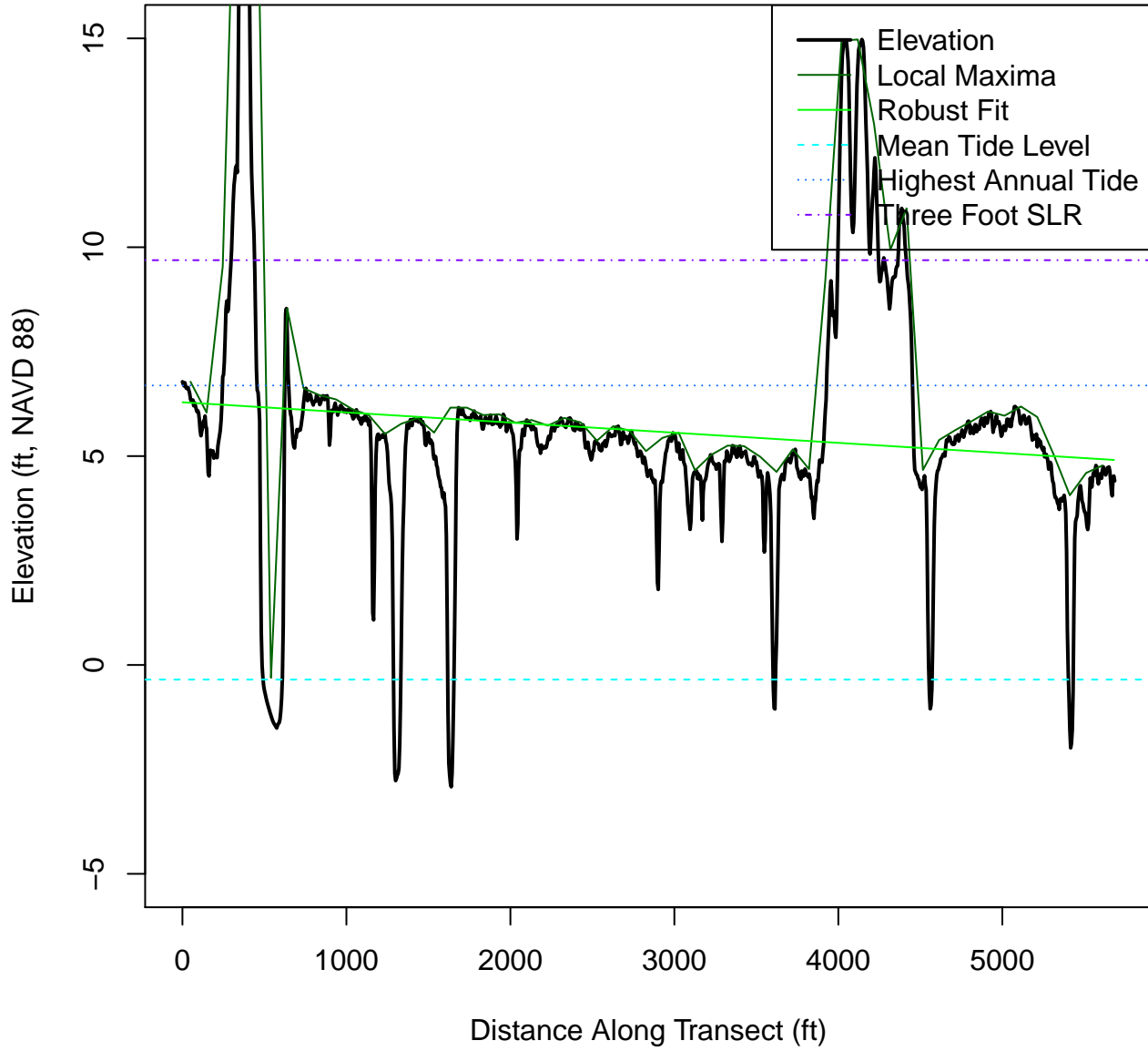
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TR109b
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**Longitudinal Profile
UNSP2
Window = 20**



**Longitudinal Profile
UNSP3
Window = 20**



Appendix B: Example Communications Materials: Brunswick, Maine

DRAFT

LAND USE PLANNING FOR SEA LEVEL RISE:

A Planner's Toolkit for Communities

Along Casco Bay, Maine

BRUNSWICK EDITION

Overview

The Intergovernmental Panel on Climate Change (IPCC) released a report in 2007 documenting a rise in average global temperatures, ocean temperatures and sea level rise. The sea level off of Maine's 3,478 miles of coastline, as measured by the Portland, Maine tide gauge, has been rising at a rate of 1.8 ± 0.1 mm/yr since 1912. This is markedly similar to the global average sea level rise determined by the IPCC. The most likely impacts of sea level rise in Maine will be inland migration of beaches, dunes and salt marshes over the next century.

Coastal wetlands are economically, environmentally and socially significant resources. They provide flood storage, flood protection, storm surge buffers, erosion control, water quality improvements, and wildlife habitat. Commercial fishing, shellfishing and outdoor recreation also contribute millions of dollars to Maine's economy and are dependent on healthy wetlands. Coastal communities and those along critical watershed areas will have to plan a comprehensive response to the changes in topography suggested by the projected impacts of sea level rise.

The unique geological make-up of Maine's coastline is characterized by very different coastal estuarine environments which are a direct result of prehistoric glacial activity. This had led geologists such as Joseph T. Kelly, to subdivide the coast into four compartments. The Casco Bay region is significantly different from the Saco Bay region, which is different from the Penobscot Bay Region as well as the far northeast region around Cobscook Bay. Thus Maine's tidal wetlands are diverse, so the impacts of and responses of those wetlands to sea level rise are likely to be markedly different in each of those four regions.

The Casco Bay watershed comprises 986 square miles, stretching from the mountains near Bethel to the coastal waters of Phippsburg and Cape Elizabeth. Home to nearly 20 percent of Maine's population, the watershed contains 42 municipalities, including some of the state's largest and fastest growing towns. The Casco Bay Estuary Partnership (CBEP), one of 28 National Estuary Programs nationwide, is a collaborative effort of people and organizations interested in protecting and restoring the Bay. Our partnership includes local, state and federal government organizations, non-profits, local businesses, citizens, universities and more.

The Study

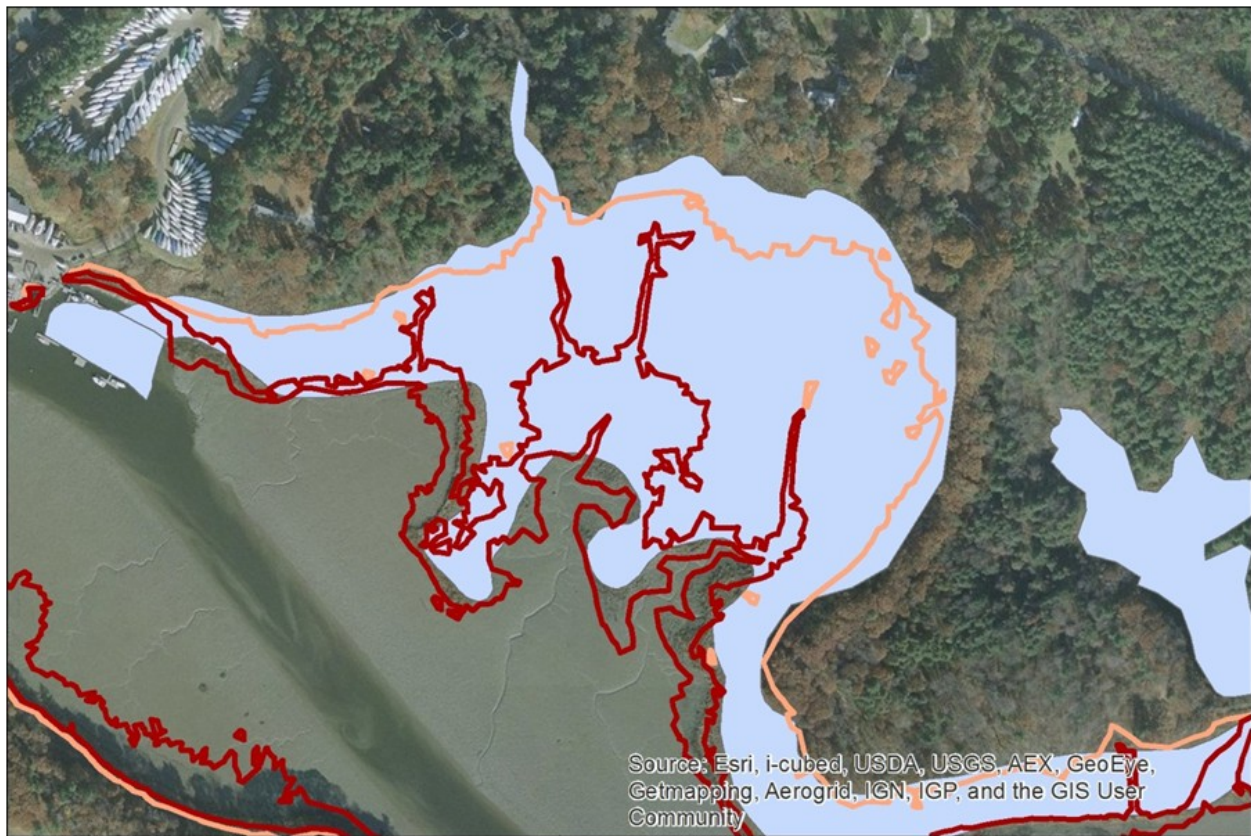
Thirteen coastal municipalities in the Casco Bay Watershed Region were included in a study which looked at potential areas of marsh migration and possible impacts to existing developed areas due to tidal inundation from projected sea level rise scenarios. A map showing the entire study area with identified areas of potential marsh migration and/or conflict with existing development can be seen in Figure 2.

The study is based on a detailed analysis of high resolution elevation data derived from "LIDAR" technologies. LIDAR is technology similar to RADAR that uses light waves instead of radio waves to measure distance from a plane to the ground. Raw LIDAR data is post-processed to produce a "Digital Elevation Model" (DEM) that shows estimated ground elevations free of buildings, trees, and other obstructions. The resulting DEM can be highly accurate, with elevations estimated every few feet, with absolute vertical errors typically less than a foot or so, and relative vertical errors much smaller than that on a local scale.

Two sources of LIDAR data were used in this analysis: (1) FEMA South Coast LIDAR 2006, (2) LIDAR for the Northeast 2011. Both data sets were acquired as DEM tiles from the University of Southern Maine's Geographic Information Systems Laboratory in spring of 2011. As received, the two data sets were based on different units of measure (feet vs. meters), so the LIDAR for the Northeast 2011 was scaled and resampled using bilinear interpolation before the two data sets were combined to produce a single composite LIDAR DEM for all of Casco Bay.

LIDAR data was combined with information on tidal heights compiled by NOAA for the Portland tide gauge in order to identify portions of the shoreline that lie within the upper intertidal zone, between the Mean Tide Level or MTL and the Highest Annual Tide, (HAT). These elevations are roughly coincident with the lower and upper limit of salt marsh development in Maine. Not every location at these elevations, however, will develop salt marsh. Salt marshes only occur where other environmental conditions are also suitable, such as having suitable soils, low slopes and low to moderate wave exposure. Nevertheless, in areas with existing tidal marsh, the overlap between existing salt marsh and areas identified solely on the basis of elevation is quite good. In the map below (Figure 1) you can see an overlay of CBEP's elevation polygons (outlined in red and orange as high and low marsh areas) compared to the National Wetlands Inventory mapped wetlands (the white areas) for a particular area in Maine. As you can see, the accuracy is certainly sufficient for the purpose of this study.

FIGURE 1



It is important to understand that the maps we have produced are not maps of flood risk, but maps of the projected upper intertidal zone. The areas highlighted in these maps are, in the absence of efforts to protect them from the ocean, expected to be flooded on a regular basis (daily to annually) due to the action of the tides. Significantly larger areas may be at risk of inundation or flooding due to storms. Because the maps we have produced to date are based solely on elevation, there may be areas in your community which show up as sitting at the proper elevation for tidal marsh development, which do not now harbor salt marshes. Typically such areas are beaches, rocky shores, or the base of steep bluffs, so there is little chance for confusion, but the maps need to be read with care.

To predict where the upper intertidal zone (and thus tidal wetland) may exist in the future, we developed similar maps showing elevations suitable for tidal marsh development under three sea level rise scenarios: one foot, two feet, and three feet of sea level rise. While these scenarios are not tied to specific climate change or sea level rise models, they are consistent with modeling efforts. A recent analysis of climate change for the Casco Bay region commissioned by CBEP suggests that increases in sea level on the order of one foot are likely by the middle of the century, while increases of two to well over three feet are possible by 2100 (See table 1).

In general, the shoreline in this region is characterized by steep rocky slopes, so we are more fortunate than our southern neighbors in that our coastline may not be as affected by tidal inundation. However, where we have mapped upper intertidal zone areas, we do see areas where existing development (as suggested by looking at 2007 data on impervious surfaces) may be vulnerable to inundation in the future or be in conflict with landward migration of tidal marshes as sea level increases.

TABLE 1:

Estimates of future stillwater elevations at the Portland tide gauge under lower and higher greenhouse gas emissions scenarios (all estimates in feet relative to NAVD 1988; based on CBEP 2010 report).

Scenario	Lower Emissions		Higher Emissions	
	2050	2100	2050	2100
Year	2050	2100	2050	2100
FEMA 1998 Stillwater Elevation	8.9	8.9	8.9	8.9
Subsidence	0.024	0.043	0.024	0.043
Dynamic	NE	0.52	NE	0.79
Eustatic	0.66	1.6	1.4	4.6
Total Predicted Stillwater Elevation (ft)	9.5	11.1	10.3	14.3
Net Change in Sea Level	0.6	2.2	1.4	5.4

Brunswick, Maine

This Toolkit is designed to help each municipality in our study area understand its risk levels, potential impacts, and to assist them in exploring possible policy-making actions for the decision-making process. The U.S. Environmental Protection Agency (EPA) produced a publication titled *Synthesis Of Adaptation Options For Coastal Areas* in January, 2009 which identifies several planning and management options for coastal communities. In a nutshell, the options available are: plan for and mitigate potential future impacts, adapt to impacts as they happen, or do nothing. In more detail, the EPA essentially divides these options into two broad categories: timing of response (proactive vs reactive), and type of response (e.g. physical, technological, institutional). The suggested options are then further organized by management goals. Although somewhat contentious, one of the newest and potentially most flexible options is to develop rolling easements. All of these options and their related action plans will be provided in this toolkit, although any option must be tailored to suit the specific needs, capacity, geomorphology, and policies of the communities which utilize them.

In Brunswick, Maine, we have identified seven primary areas as being at risk of conflict between rising seas and existing developed areas and/or areas where we see potential marsh migration.

These areas are identified as:

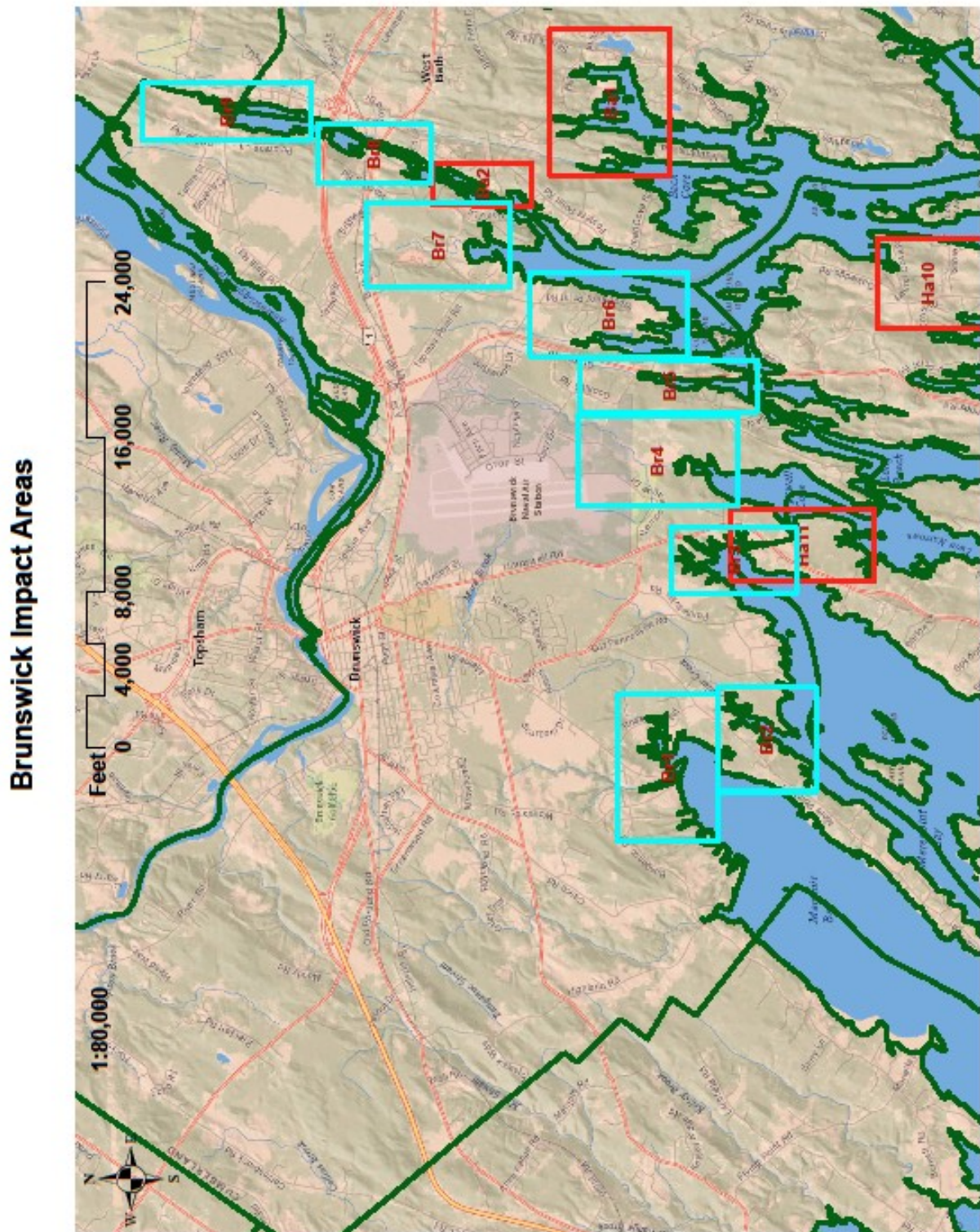
1. Maquoit Bay
2. Merepoint Bay
3. Middle Bay
3. Harpswell Cove
4. Buttermilk Cove
5. Woodward Cove
6. Thomas Bay
7. Bridge to Bath
8. New Meadows River

Two maps were produced for each area:

1. Areas of concern for conflict between existing development and a one-foot sea level rise
2. Areas of concern for conflict between existing development and a three-foot sea level rise

A map of the entire Brunswick area can be seen in Figure 3. Each area of concern is outlined in blue and identified by the abbreviation Br and its assigned number. As mentioned previously, caution must be taken when interpreting these maps as some of the areas may or may not pose any serious future risk for tidal inundation. Local knowledge of these areas will be necessary to more accurately gauge whether or not they are areas of concern for Brunswick according to current or future development plans, comprehensive plans, or conservation plans. Some areas may pose concern in regard to existing or future infrastructure and other areas may see more significant changes in regard to wetland type and, subsequently, habitat. Below is a brief description of why each area was chosen in order to facilitate further consideration and dialog.

FIGURE 3



Br1: Maquoit Bay

Figures 4 and 5 show areas in Maquoit Bay that are potentially in conflict with development due to a one foot rise and a three foot rise in sea level, respectively. Areas in blue are where current wetlands exist and areas in yellow are where wetlands may disappear. The areas in orange show potential inland marsh migration that do not seem to pose a conflict with current development. The areas in pink show potential marsh migration into areas where there is existing development that may be in conflict from tidal inundation. When you compare Figures 4 and 5, you will notice that wetland areas which are adjacent to water will begin to disappear under the surface of rising sea levels and so you may see some loss of wetlands in those particular locations as marshes begin to move inland. However, when you look at the 3 foot sea level rise projection, you will also notice an increase in marsh area upland. The result may be a zero net gain or loss of wetlands as they migrate inward. Regardless, the migration of these wetland areas may impact existing roads such as Rossmore, Maquoit and Woodside.

Br2: Merepoint Bay

Figures 6 and 7 show areas in Merepoint Bay that are potentially in conflict with development due to a one foot rise and a three foot rise in sea level, respectively. Areas in blue are where current wetlands exist and areas in yellow are where wetlands may disappear. The areas in orange show potential inland marsh migration that do not seem to pose a conflict with current development. The areas in pink show potential marsh migration into areas where there is existing development that may be in conflict from tidal inundation. When you compare Figures 6 and 7, you will notice that wetland areas which are adjacent to water will begin to disappear under the surface of rising sea levels and so you may see some loss of wetlands in those particular locations as marshes begin to move inland. However, when you look at the 3 foot sea level rise projection, you will also notice an increase in marsh area upland. The result may be a zero net gain or loss of wetlands as they migrate inward. We do not see much conflict with existing development except for the tidal barrier labeled as a road on these two maps. This item which is indicated as a tidal barrier is actually a foot bridge but it may be at risk of getting flooded over with a rise in sea level.

Br3: Middle Bay

Figures 8 and 9 show areas in Middle Bay that are potentially in conflict with development due to a one foot rise and a three foot rise in sea level, respectively. Areas in blue are where current wetlands exist and areas in yellow are where wetlands may disappear. The areas in orange show potential inland marsh migration that do not seem to pose a conflict with current development. The areas in pink show potential marsh migration into areas where there is existing development that may be in conflict from tidal inundation. When you compare Figures 8 and 9, you will notice that wetland areas which are adjacent to water will begin to disappear under the surface of rising sea levels and so you may see some loss of wetlands in those particular locations as marshes begin to move inland. However, when you look at the 3 foot sea level rise projection, you will also notice an increase in marsh area upland. The result may be a zero net gain or loss of wetlands as they migrate inward. Perhaps the most notable difference between these two maps is seen in Map 9 where, if you look at the south end of Middle Bay, you can see that the wetland area begins to touch the nearby wetland area from Skolfield Cove. The migration of marsh area joining the marsh area by Skolfield Cove may impact Route 123 in addition to possible impacts further up Route 123 where you may see some marsh migration upland.

Br4: Harpswell Cove

Figures 10 and 11 show areas in Harpswell Cove that are potentially in conflict with development due to a one foot rise and a three foot rise in sea level, respectively. Areas in blue are where current wetlands exist and areas in yellow are where wetlands may disappear. The areas in orange show potential inland marsh migration that do not seem to pose a conflict with current development. The areas in pink show potential marsh migration into areas where there is existing development that may be in conflict from tidal inundation. When you compare Figure 10 to Figure 11, you will notice that the tributary which extends up from Harpswell Cove begins to increase in size and length. Although there is a small amount wetland loss at a 3 foot sea level rise, the increase in marsh area is most notable. At the 3 foot sea level rise projection, you will see that the migration of this wetland area may impact existing roads such as Liberty Crossing and Ordinance Road as well as the golf course to the west of the marsh land.

Br5: Buttermilk Cove

Figures 12 and 13 show areas in Buttermilk Cove that are potentially in conflict with development due to a one foot rise and a three foot rise in sea level, respectively. Areas in blue are where current wetlands exist and areas in yellow are where wetlands may disappear. The areas in orange show potential inland marsh migration that do not seem to pose a conflict with current development. The areas in pink show potential marsh migration into areas where there is existing development that may be in conflict from tidal inundation. When you compare Figure 12 to Figure 13, you will see a small amount wetland gain and loss at a 3 foot sea level rise, but it does not appear to be significant. You will see, however, that the migration of this wetland area may impact existing roads such as Princes Point Road, Route 24 and Coombs Road.

Br6: Woodward Cove

Figures 14 and 15 show areas in Woodward Cove that are potentially in conflict with development due to a one foot rise and a three foot rise in sea level, respectively. Areas in blue are where current wetlands exist and areas in yellow are where wetlands may disappear. The areas in orange show potential inland marsh migration that do not seem to pose a conflict with current development. The areas in pink show potential marsh migration into areas where there is existing development that may be in conflict from tidal inundation. Although there is a small amount wetland gain and loss at a 3 foot sea level rise, this does not appear to be significant. It appears that there may be some conflicts on the north end of Upper Coombs Island. However, the Kimberly Circle area as well as the residential and Route 24 areas at the tip of the marsh may also see future impacts due to marsh migration close to homes and roads.

Br7: Thomas Bay

Figures 16 and 17 show areas in Thomas Bay that are potentially in conflict with development due to a one foot rise and a three foot rise in sea level, respectively. Areas in blue are where current wetlands exist and areas in yellow are where wetlands may disappear. The areas in orange show potential inland marsh migration that do not seem to pose a conflict with current development. The areas in pink show potential marsh migration into areas where there is existing development that may be in conflict from tidal inundation. Although there is a small amount wetland loss at a 3 foot sea level rise, this does

not appear to be significant. There does appear to be a significant amount of new marsh area created between the eastern side of Thomas Bay around Howard's Point. Most of the conflict with existing development occurs near Howard's Point Lane, Thomas Point Beach Road, Adams Road, Varney Lane, Cranberry Drive which leads to the Mid Coast Hospital, and Hale Street next to Bath Road.

Br8: The Bridge to Bath

Figures 18 and 19 show areas around the bridge to Bath that are potentially in conflict with development due to a one foot rise and a three foot rise in sea level, respectively. Areas in blue are where current wetlands exist and areas in yellow are where wetlands may disappear. The areas in orange show potential inland marsh migration that do not seem to pose a conflict with current development. The areas in pink show potential marsh migration into areas where there is existing development that may be in conflict from tidal inundation. The most significant area of concern is the area around Bath Road where a 3 foot sea level rise may impact the New Meadows Marina as well as other commercial and residential property and roads in that area and in the area between Bath Road and the Railroad tracks.

Br9: New Meadows River

Figures 20 and 21 show areas around the New Meadows River that are potentially in conflict with development due to a one foot rise and a three foot rise in sea level, respectively. Areas in blue are where current wetlands exist and areas in yellow are where wetlands may disappear. The areas in orange show potential inland marsh migration that do not seem to pose a conflict with current development. The areas in pink show potential marsh migration into areas where there is existing development that may be in conflict from tidal inundation. The most striking difference you will notice is a significant loss of wetland north of Old Bath Road which is projected to be inundated from sea level rise at the 3 foot sea level rise scenario. There may be some conflict with existing development on an unidentified parcel located off of Bridge Road.

FIGURE 4

Brunswick Maquoit Bay: 1 ft. Sea Level Rise

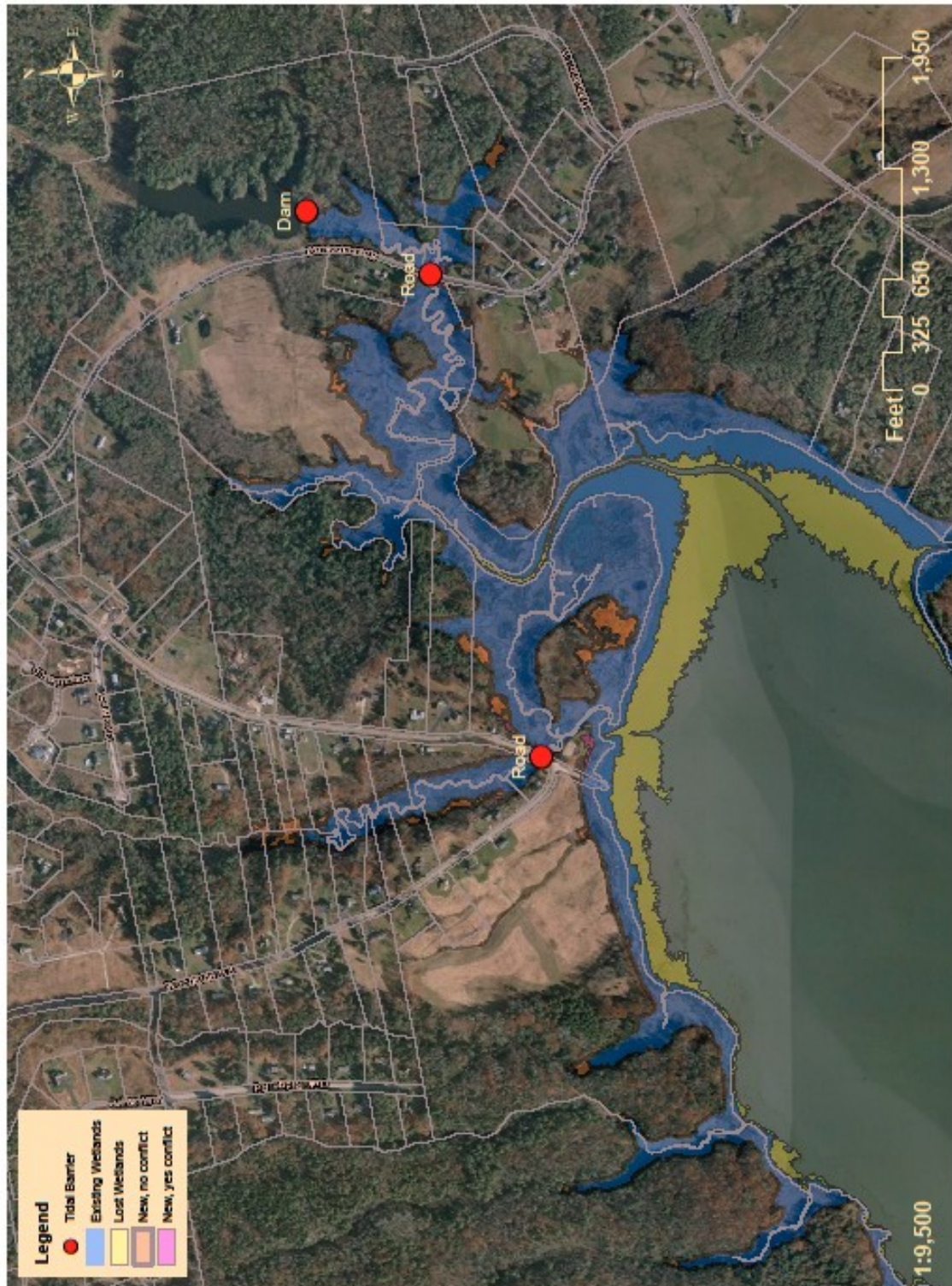


FIGURE 5

Brunswick Maquoit Bay: 3 ft. Sea Level Rise



FIGURE 6

Brunswick Merepoint Bay: 1 ft. Sea Level Rise



FIGURE 7

Brunswick Merepoint Bay: 3 ft. Sea Level Rise



FIGURE 8

Brunswick Middle Bay: 1 ft. Sea Level Rise



FIGURE 9 Brunswick Middle Bay: 3 ft. Sea Level Rise



FIGURE 10 Brunswick Harpswell Cove: 1 ft. Sea Level Rise



FIGURE 11 Brunswick Harpswell Cove: 3 ft. Sea Level Rise

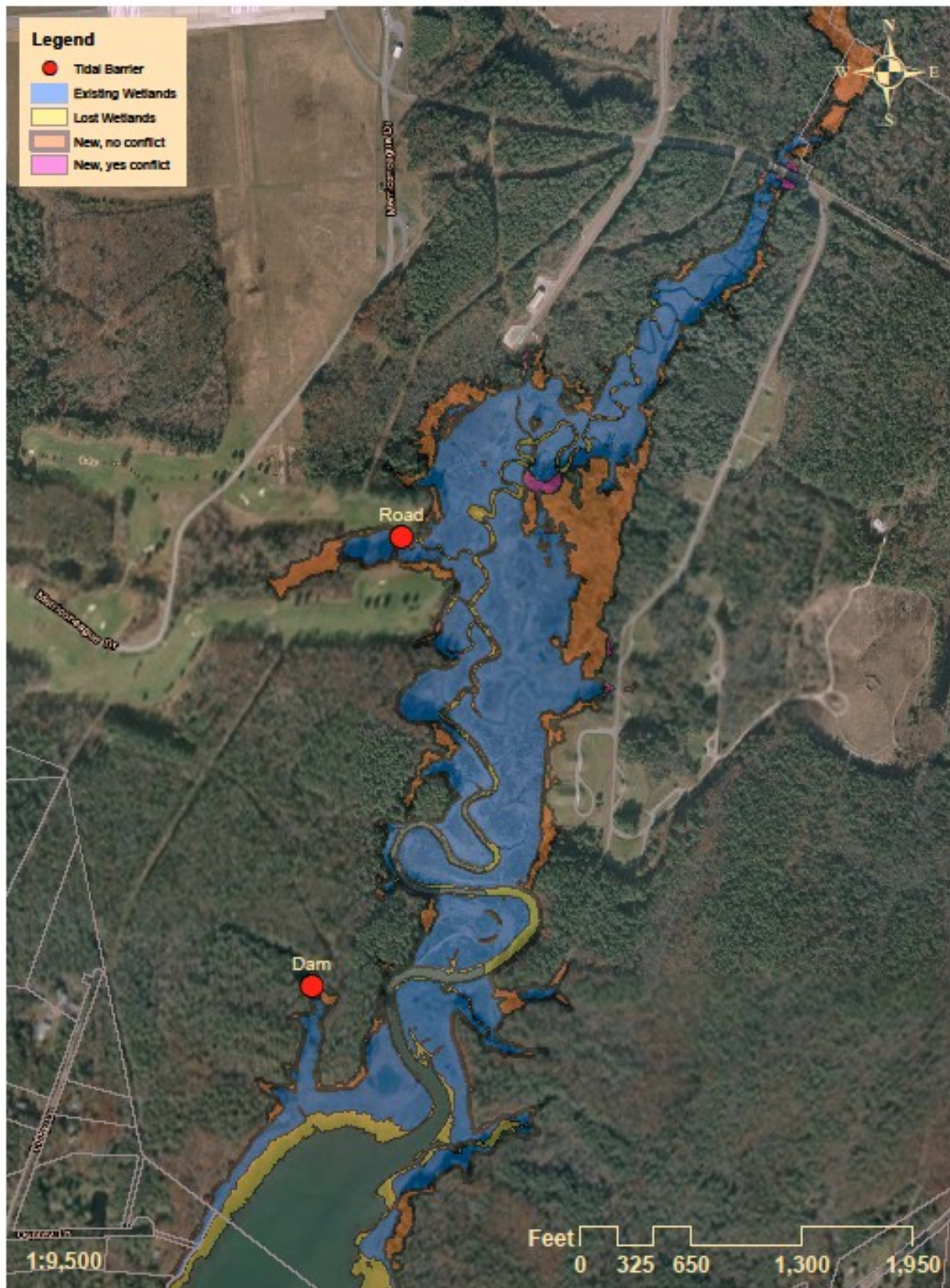


FIGURE 12 Brunswick Buttermilk Cove: 1 ft. Sea Level Rise



FIGURE 13 Brunswick Buttermilk Cove: 3 ft. Sea Level Rise

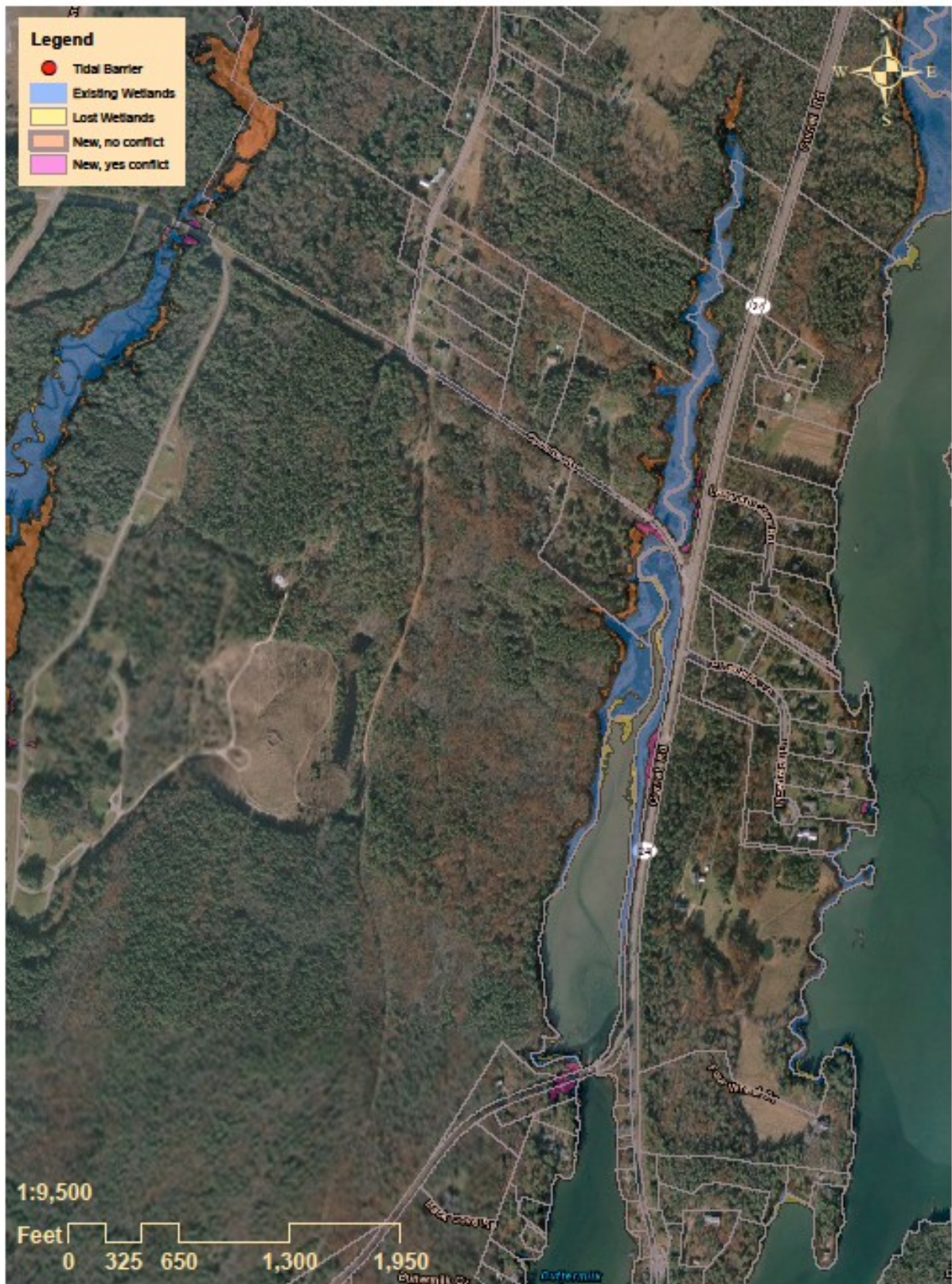


FIGURE 14 Brunswick Woodward Cove: 1 ft. Sea Level Rise

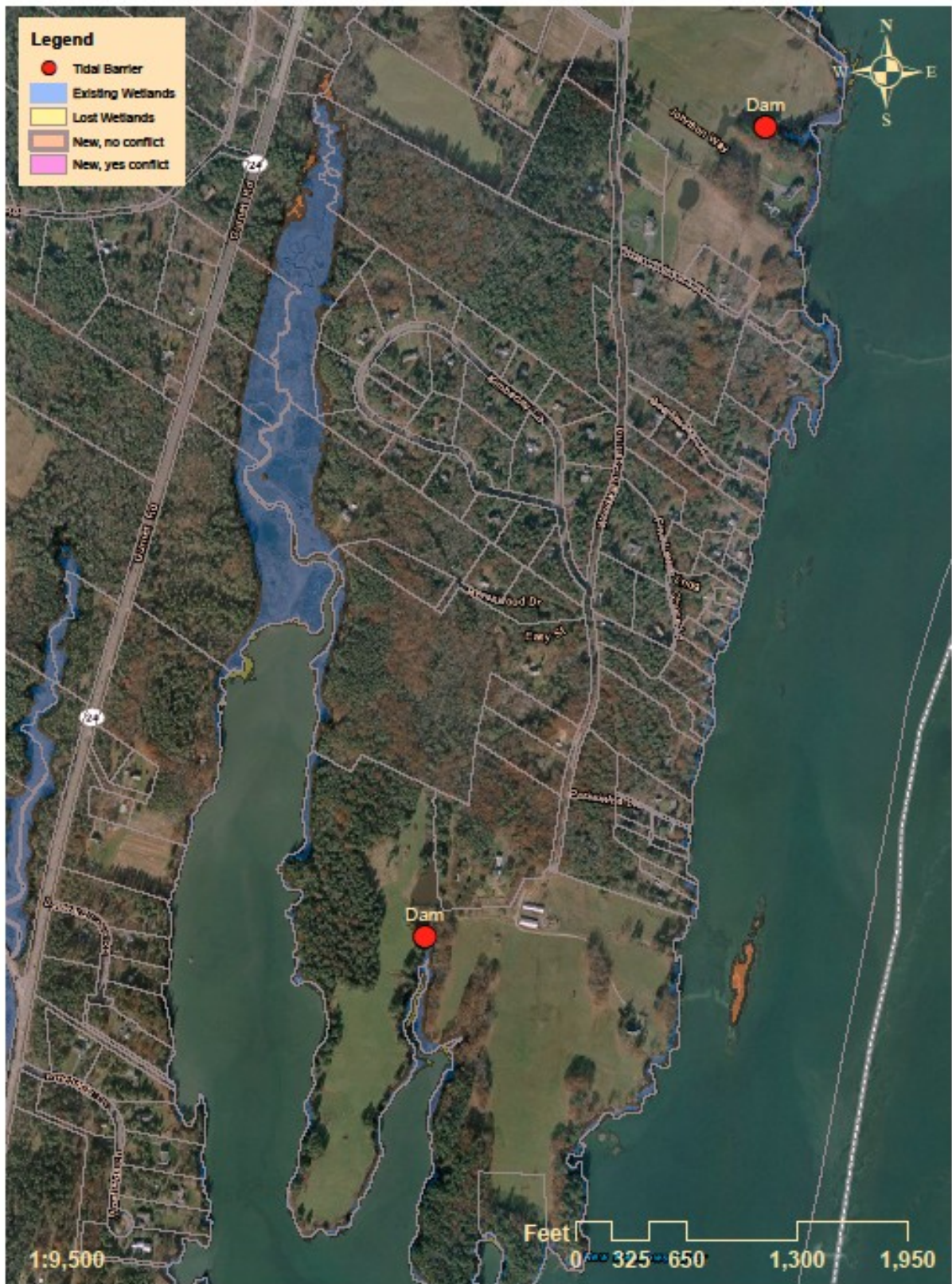


FIGURE 15 Brunswick Woodward Cove: 3 ft. Sea Level Rise

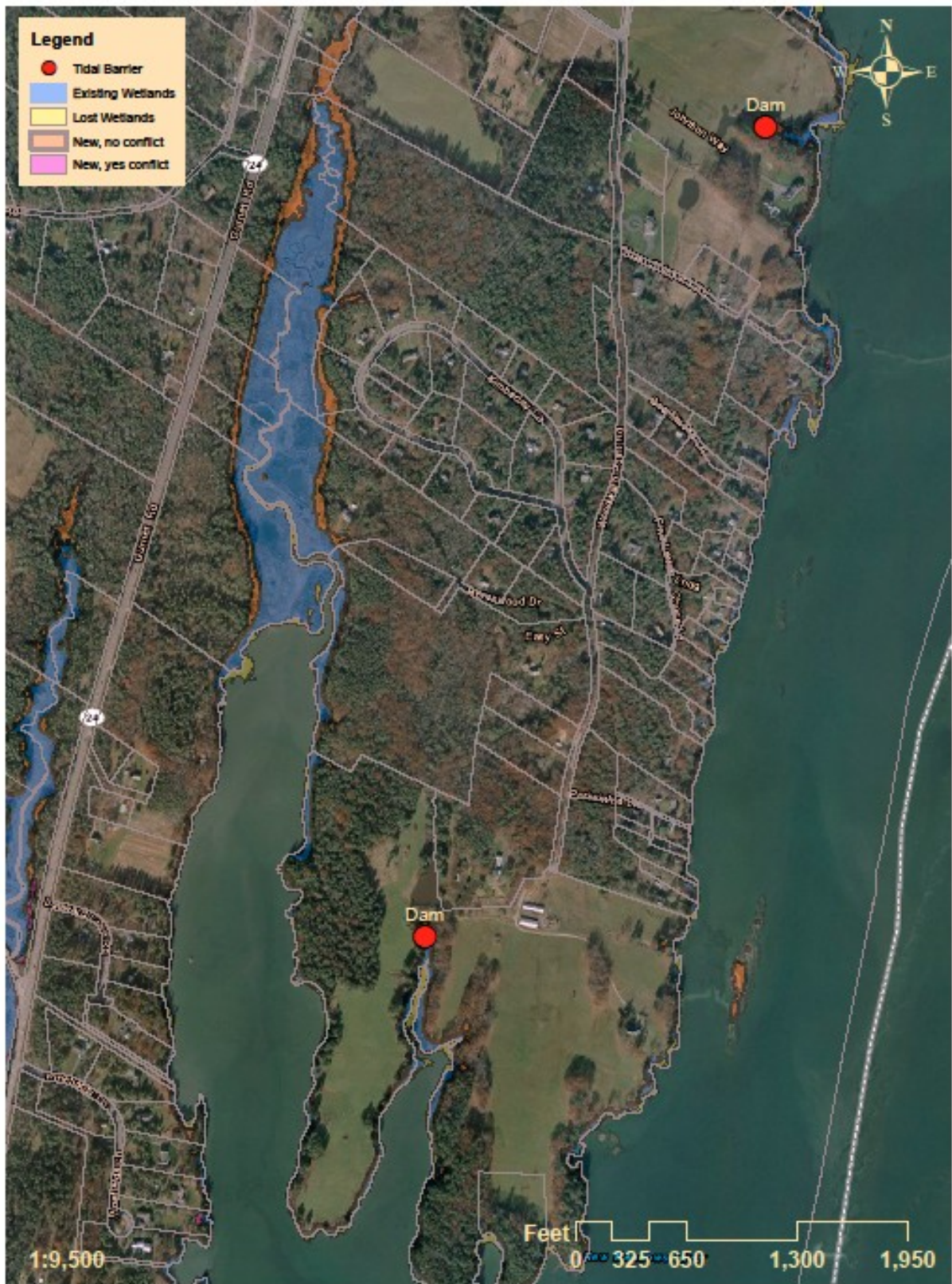


FIGURE 16 Brunswick Thomas Bay: 1 ft. Sea Level Rise



FIGURE 17 Brunswick Thomas Bay: 3 ft. Sea Level Rise



FIGURE 18

Brunswick Bridge to Bath Area: 1 ft. Sea Level Rise

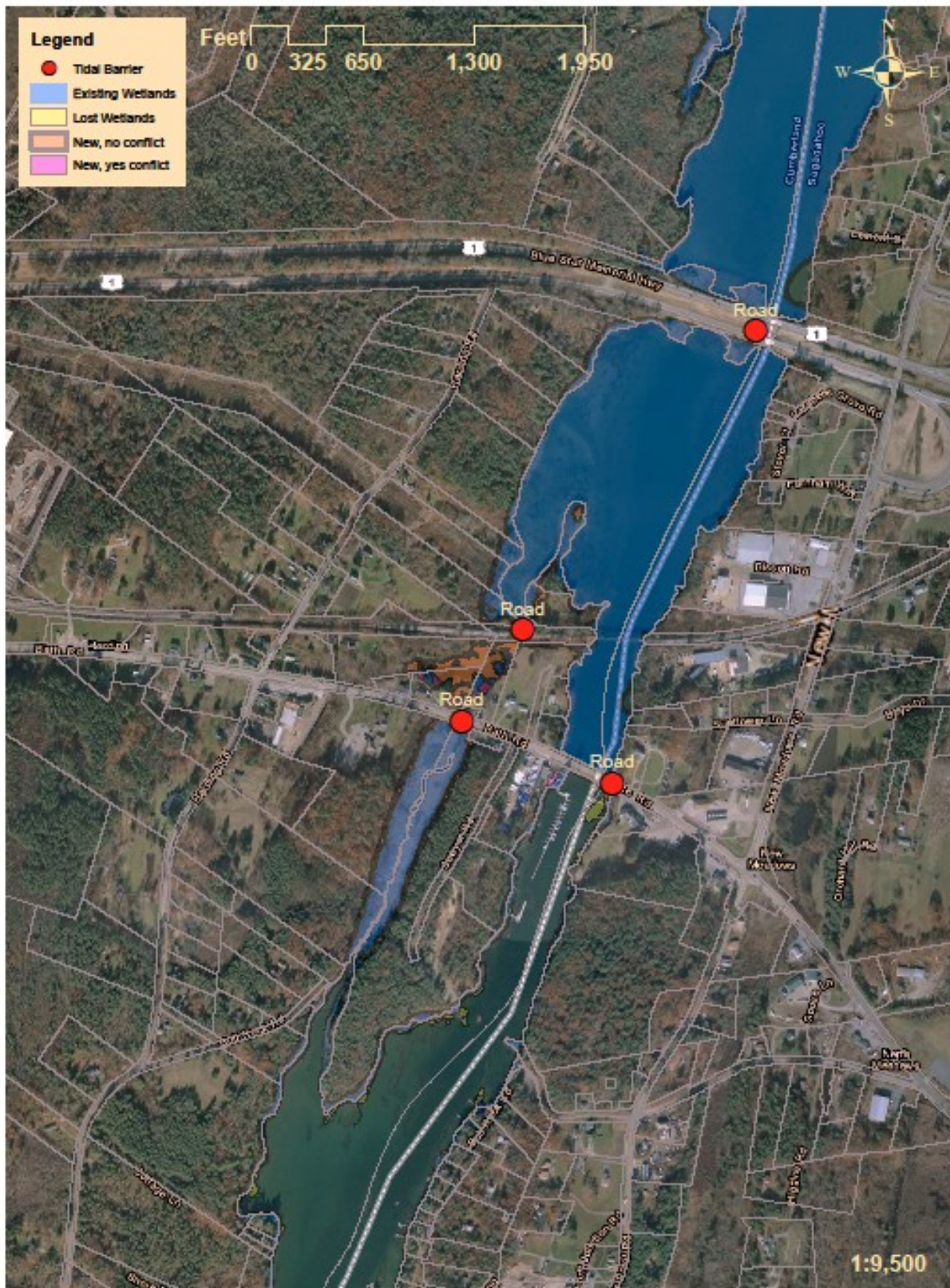


FIGURE 19

Brunswick Bridge to Bath Area: 3 ft. Sea Level Rise

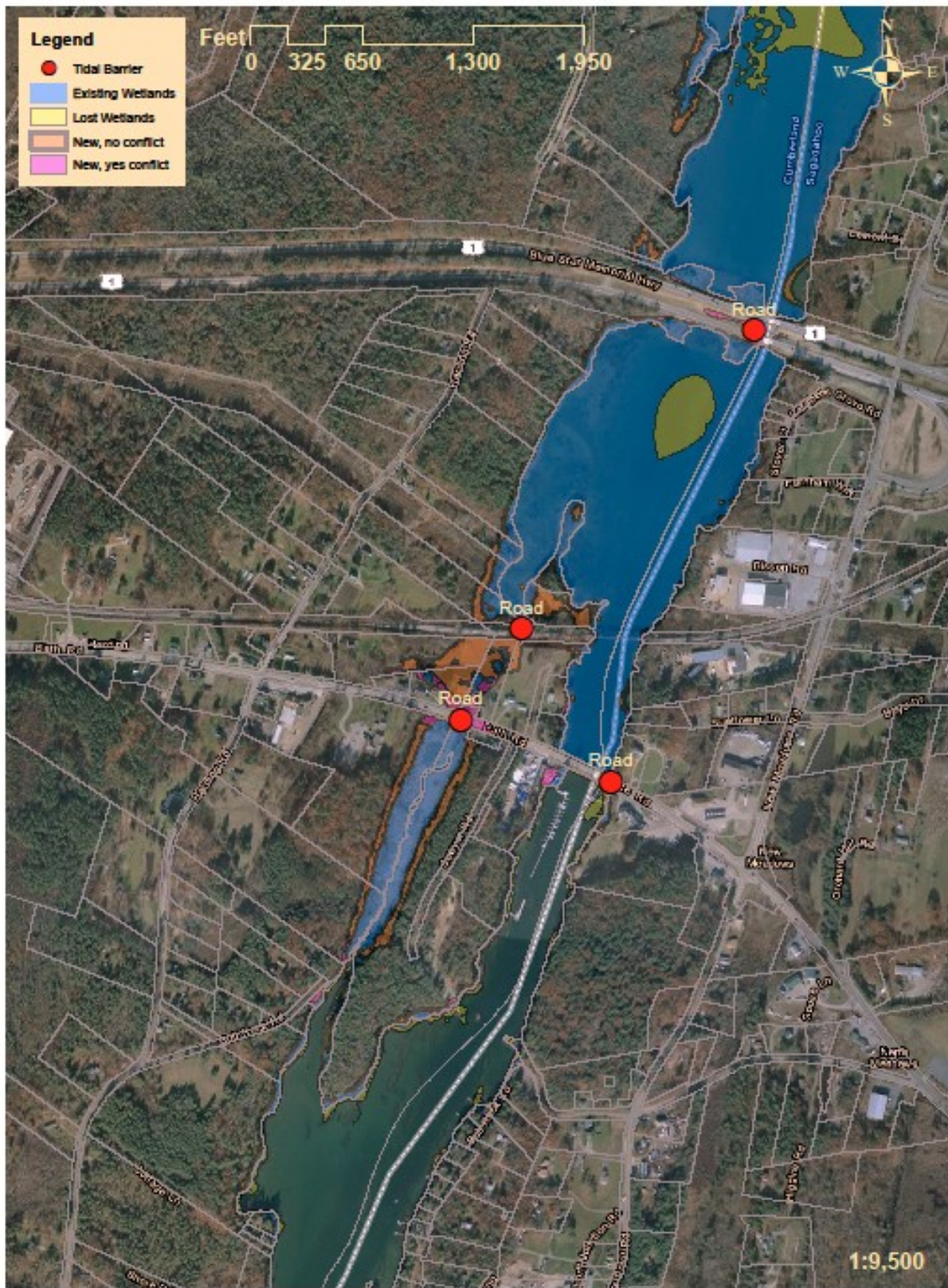


FIGURE 20

Brunswick New Meadows River: 1 ft. Sea Level Rise

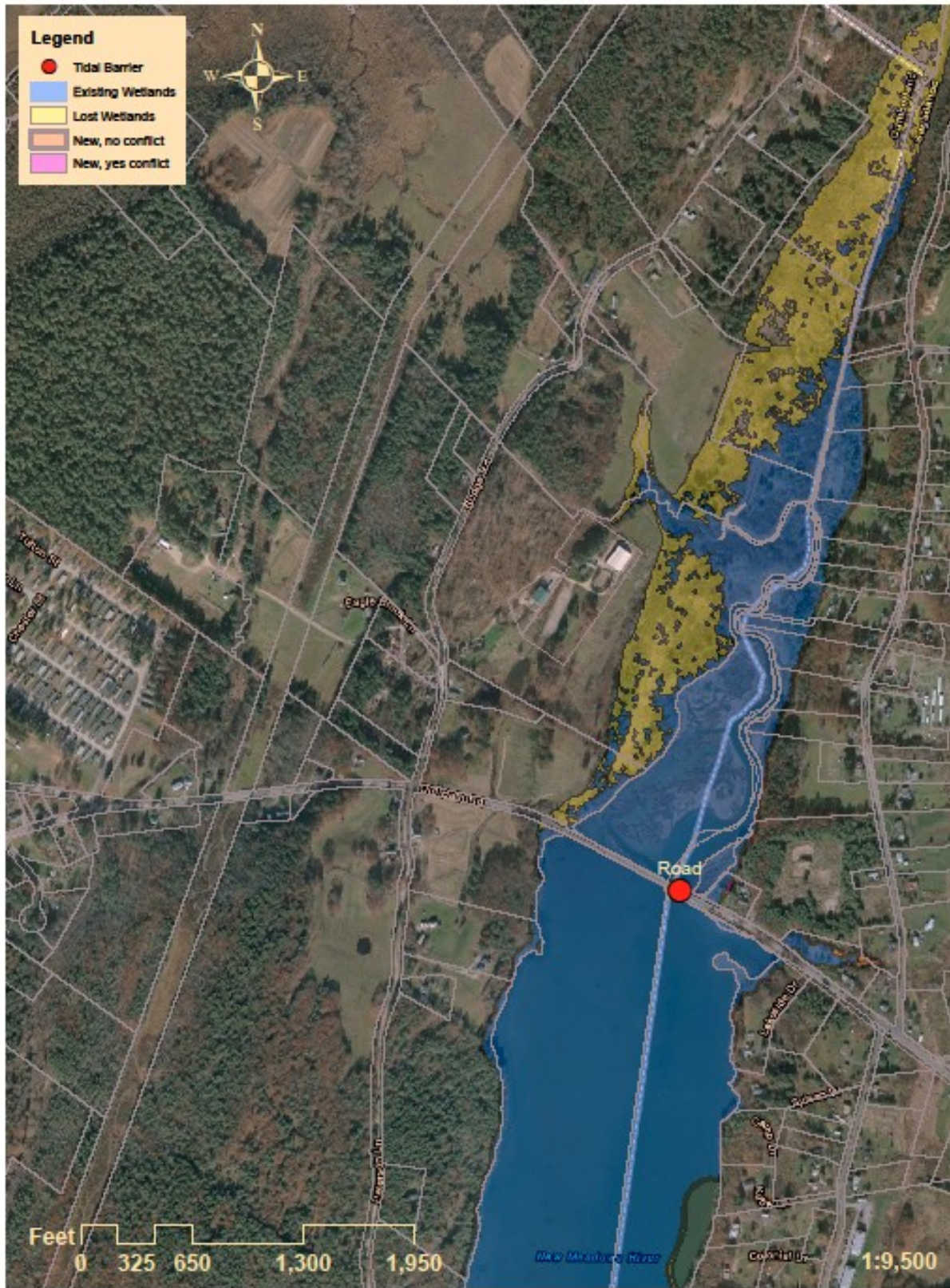


FIGURE 21

Brunswick New Meadows River: 3 ft. Sea Level Rise

