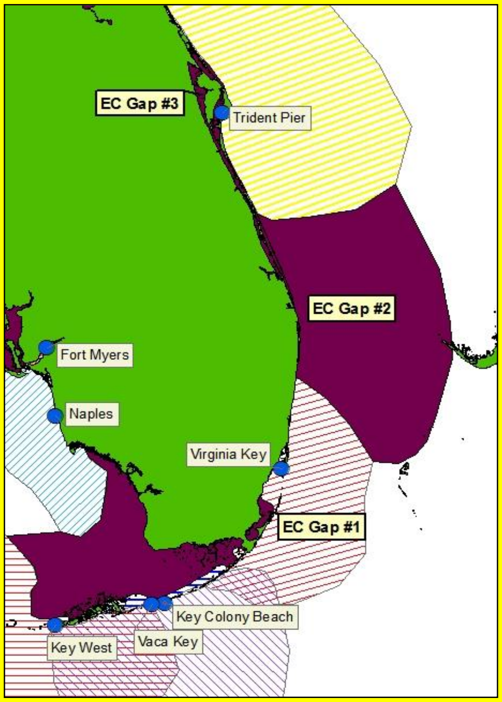
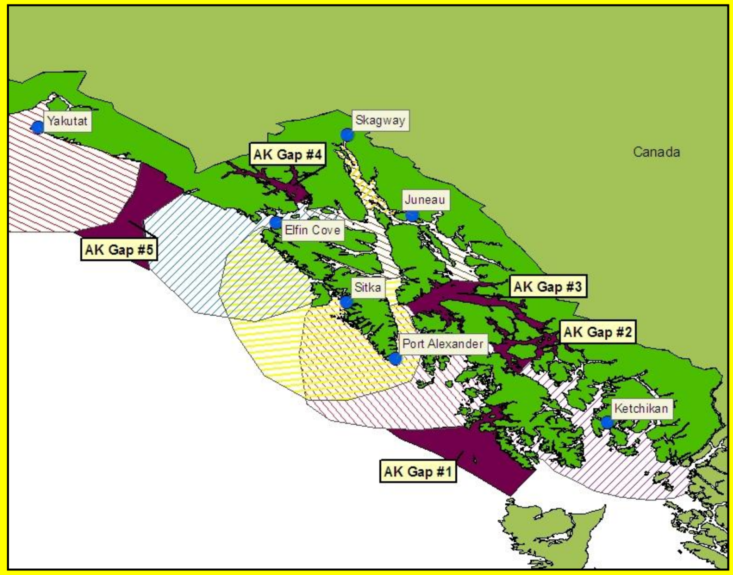
NOAA Technical Memorandum NOS CO-OPS 0048

A NETWORK GAPS ANALYSIS FOR THE NATIONAL WATER LEVEL OBSERVATION NETWORK – Updated Edition





Silver Spring, Maryland
September 2014

noaa **National Oceanic and Atmospheric Administration**

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services

Center for Operational Oceanographic Products and Services
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

The National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) provides the National infrastructure, science, and technical expertise to collect and distribute observations and predictions of water levels and currents to ensure safe, efficient and environmentally sound maritime commerce. The Center provides the set of water level and tidal current products required to support NOS' Strategic Plan mission requirements, and to assist in providing operational oceanographic data/products required by NOAA's other Strategic Plan themes. For example, CO-OPS provides data and products required by the National Weather Service to meet its flood and tsunami warning responsibilities. The Center manages the National Water Level Observation Network (NWLON), a national network of Physical Oceanographic Real-Time Systems (PORTS®) in major U. S. harbors, and the National Current Observation Program consisting of current surveys in near shore and coastal areas utilizing bottom mounted platforms, subsurface buoys, and horizontal mounted sensors. The Center: establishes standards for the collection and processing of water level and current data; collects and documents user requirements which serve as the foundation for all resulting program activities; designs new and/or improved oceanographic observing systems; designs software to improve CO-OPS' data processing capabilities; maintains and operates oceanographic observing systems; performs operational data analysis/quality control; and produces/disseminates oceanographic products.

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Updated Edition September 2014
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Stephen K. Gill

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

An updated assessment of the size and geospatial density of water level stations for the National Water Level Observation Network (NWLON) has been completed. The original gaps analysis report was first published in 2008. The reports provide a rationale for the number of and location of NWLON stations that are required to support NOAA Missions and Goals. The analysis results have identified approximately 111 gaps in NWLON coverage beyond the 210 NWLON stations deployed as of FY2014. Forty-three (43) gaps are located along the east coast, 28 in the gulf coast, 6 gaps on the west coast, 32 gaps in Alaska, and 2 in Hawaii. The 111 NWLON gaps identified in this report plus the three (3) NWLON gaps identified in the Great Lakes NWLON results in a total of 114 NWLON gaps. Added to the existing 210 NWLON stations, the approximate target NWLON size is 324 stations.

A NETWORK GAPS ANALYSIS FOR THE NATIONAL WATER LEVEL OBSERVATION NETWORK

PURPOSE

The purpose of this report is to provide an updated deterministic assessment of the size and geospatial density of water level stations for the National Water Level Observation Network (NWLON). The original report first published in March 2008 (Gill and Fisher 2008). It provides a rationale for the number of and location of NWLON stations that is required to support NOAA Missions and Goals. The report identifies specific locations where network gaps exist. Several gaps identified in the original report have been since filled with new NWLON stations and further refinement of the NWLON gaps has been made, primarily in the arctic region. A companion technical report NOS CO-OPS 0074 (Gill, 2014) assessing the Great Lakes component of the NWLON has also been published simultaneously to provide a complete assessment of the entire NWLON.

INTRODUCTION

An observing system network can be a system of interconnected measurement points that provides information over a desired geographical area, such that variations in the desired observational parameters can be fully described and understood and the information can be continuously obtained and applied. For good network design, considerations must be made for redundancy and backup at each of the measurement points, and the design must consider overlap and backup coverage for a particular measurement point if it stops operating or data are lost.

The Center for Operational Oceanographic Products and Services (CO-OPS) is responsible for managing the National Water Level Observation Network (NWLON) to meet NOAA's present and future mission requirements for national tide and water level data. The NWLON is recognized as a major component of the federal ocean observing system backbone for the nation, providing a baseline network of water level measurements and a national reference system for water level derived vertical datums that can be used to dovetail with other Federal, State, academic, and private and public sector water level requirements. The recently published National Plan for Civil Earth Observations by the White House Office of Science and Technology Policy (http://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/national_plan_for_civil_earth_observations_-_july_2014.pdf) is a first ever comprehensive evaluation of all U.S. earth observing systems to provide a framework for constructing a balanced portfolio of Earth observations and observing systems. Out of 362 systems evaluated, the NWLON was one of 15 that were identified as being Tier 1; systems having high impact on a majority of societal benefit areas.

The NWLON must provide for the density of information required to describe water level variations at all appropriate time and geographic scales. This density is described in terms of geographic coverage of a particular measurement location. Time scales range from short-term (real-time) data for navigation to long term (decades to centuries) data for estimation of relative sea level trends and for updates to National Tidal Datum Epochs (NTDE). The geographic scales required include the need for regional coverage of significant variations in tidal characteristics and gradients in relative sea level trends. Depending upon specific requirements, water level stations can be either short-term (one year or less) or long term (one-year to several decades). The overall program design is a blend of long-term (control) stations and shorter-term (subordinate) stations (one-month to several year occupations) that provide localized information to specific areas for specific applications.

Based on operational experience in planning of hydrographic, shoreline and coastal engineering projects and cumulative knowledge from project analyses, there is empirical knowledge of coastal areas that lack or have inadequate control for datum determination. Several qualitative assessments of NWLON coverage have also been completed over the years (NOS, 1986). This gaps analysis report provides a quantitative scientific assessment of the geographic gaps in NWLON coverage using an error analyses approach to identify the gaps.

This revised edition provides an update to the 2008 report (Gill and Fisher) by:

1) Accounting for new NWLON stations established since the first report and updating coverage polygons.

2) Aligning the gap polygons with the projected number of new station (several gaps were previously identified that actually required more than one station).

3) Taking a more comprehensive look a impacts of relative sea level variations on identified gaps

NETWORK DESIGN

The requirements of the NWLON can be thought of as a set of layers, with each layer having its own needs for coverage; that is the number and placement of water level stations. These layers of requirements can be described as two fundamental information layers followed by five application layers:

Fundamental layers, determination of:

Layer 1) Tidal and Water Level Datums

Layer 2) Relative Sea Level Trends and Climate Change

Applications layers, support for:

Layer 3) Marine Transportation System Operations

Layer 4) Nautical Charting Program: Hydrographic Surveying and Shoreline Mapping

Layer 5) Storm Surge Inundation, Emergency Evacuation, and Tsunami Warning

Layer 6) Habitat Restoration, Coastal Resource Management, Coastal Engineering, and Environmental Monitoring

CO-OPS Special Publication *Tidal Datums and Their Applications* (NOS, 2001) provides summaries of the major applications. Layers 1) and 2) are the focus of this report as the determination of tide and water level datums and sea level trends are fundamental to the successful application of the data to Layers 3) through 6). Layers 2 through 6 are used for priority setting, for development of partnerships, and for making operational decisions for the status of station repairs and /or replacement. For Layer 2) a subset of long-term remote ocean island stations and key coastal NWLON stations contribute to the Global Sea Level Observing System (GLOSS) and work in partnership with the NOAA Climate Program Office to enhance products and services for climate monitoring and research and to integrate our long-term data sets with geodesy to support determination of global sea level change. The NWLON is supplemented by short-term stations to provide more precise and accurate coverage in between NWLON stations to meet the needs of these application layers. Marine Transportation System Operations (Layer 3) requirements are met through programs such as the Physical Oceanographic Real Time System (PORTS®), a localized real-time observing system designed and established in partnership with local maritime constituencies. Layers 3 and 4 are interconnected through the Nautical Charting and Shoreline Mapping Programs. The NWLON has been increasingly enhanced to meet the needs of the hazards warning and response community (Layer 5) both through improved communications and high rate measurement capability, new sensors, and with new station placement. This has been accomplished in partnership with NOAA's National Weather Service (NWS), Tsunami Warning Centers

(TWC's), and local partners. CO-OPS delivers tailored products to the non-navigation community (Layer 6) such as the need for habitat restoration and planning and for environmental monitoring

Layer 1) Tide Control

This layer describes the coverage necessary to meet requirements for a national vertical reference system for tide and water level datums. The network must be able to provide reliable, accurate information on tide and water level datums for all areas of the nation's coasts. As mentioned before, the NWLON is a network of long-term continuously operating water level stations that provides the fundamental baseline of the national reference system for tide and water level datums. The overall network design is a blend of long-term NWLON stations and shorter-term stations (operational one-month to several years) that provide project specific localized datum information. Together, these long-term and short-term stations and the derived products comprise a tidal datum reference system for the nation.

The time period necessary to incorporate all of the major astronomical tide producing cycles into the computation of a tidal datum is 19-years. All tidal datums are referenced to specific 19-year National Tidal Datum Epochs (NTDE). The present NTDE is 1983-2001. NTDE datums for short-term stations are computed and adjusted to the NTDE using simultaneous comparison with an appropriate nearby control station (NOS, 2003 and Marmer, 1951). The NWLON stations generally serve as the control stations for tidal datum determination at nearby short-term stations. Appendix 1 is a table of the locations of the present long-term NLWON excluding the Great Lakes (see Gill, 2014). Appendix 3 provides information on the physical configuration of a typical NWLON station.

Layer 2) Relative Mean Sea Level Trends

As mentioned above, the NWLON design must also account for variations in relative trends in mean sea level along the coast. Even though tidal characteristics may vary similarly across large regions in a particular region, if the sea level trends change significantly, then the determination of the tidal datums at a given location using a specific control station will still be limited. Inferring similar relative mean sea level trends at control/subordinate station pairs during the datum computation process will bias the computed datum at the subordinate station if the trends are not the same. The estimates of relative sea level trends found in Zervas (2009) are operationally used to estimate errors in tidal datum elevations if sea level trends are not properly taken into account and are used to assess the need to update to a new National Tidal Datum Epoch (NTDE) time period. NTDE periods are assessed for potential update on a nation-wide basis every few decades based on analyses of relative sea level trends. Appendix 2 shows maps of NWLON locations, NWLON gaps and sea level trends (see discussion in later sections).

PROJECT SCOPE AND IMPACT

For marine boundary purposes and coastal marsh restoration projects, accurate delineation of the location of tidal datums elevations relative to the land, the surveying user community desires datum elevations to 0.10ft (0.033m) uncertainty (95%CI). This is because a very slight slope in the beach or water front surface will result in a boundary line location or a plant species inundation tolerance threshold different by several feet in the horizontal if the vertical elevation is in error or not precise. Real-time navigation users are now interested in more accurate water levels relative to accurate chart datum and channel depth reference systems because larger and larger vessels with deeper drafts and smaller bridge clearances are now coming into most ports. Elevations previously at the several tenths of a foot uncertainty are now desired to the nearest 0.10 ft. for marine operations as well.

The accuracy of tidal datum computations at these subordinate stations depends upon an NWLON with proper geographic spacing and density. This report does not cover the remote ocean island tide stations (i.e. Guam, Kwajalein), as these islands have relatively short coastlines requiring coverage and there is little change in tidal characteristics and sea level trends around each island. Requirements for these stations are highly driven by climate needs (monitoring global climate change and oscillations such as El Nino Southern Oscillation (ENSO) and international Global Sea level Observing Systems (GLOSS).

The technique for determining gaps used in this report does not apply in the Great Lakes because they are essentially non-tidal and are dominated by short-term water level variability due to weather and longer – term variability due to seasonal hydrologic conditions.. The analysis of gaps requires a much different methodology and separate gaps analysis has been completed (Gill, 2014). The NWLON stations in the Great Lakes provide coverage for water level datum transfers to short-term stations, for hydraulic corrector calculation, and for seasonal water level forecasts.

This gaps analysis attempts to determine the distribution and number of NWLON stations required to provide continuous and overlapping coverage of the coast to meet mission requirements. For this study, coverage is defined by the geographic area in which a particular station can provide accurate control for the determination of tidal datums.

The NWLON network design is driven by an error analyses for the uncertainty in knowing tidal datum elevations to the confidence level demanded by the multiple user applications expressed by Layers 3-6 described earlier in *Network Design*. These errors are in turn driven by the geospatial changes in tidal characteristics (differences in time and range of tide) and changes in relative sea level trends. The NWLON network must be designed to provide sufficient coverage for these changes. Figure 1 displays the area wide complexity of the tide, exhibited by the co-range (GT, or Diurnal Range) and co-time lines (TcLLWI, or Tropic Lower Low Water Interval) for the northern Gulf of Mexico. In addition, the network must be designed to provide appropriate levels of redundancy or overlap. This provides a nearby backup station for datum determination without a severe loss in accuracy if a station goes down. Complete loss of data from a NWLON station is rare, as backup sensors, redundant data collection paths, and real-time quality control systems are in place (see Appendix 3). However, unavoidable losses sometimes occur when stations are destroyed when in the eye-paths of hurricanes or damaged by coastal storms.

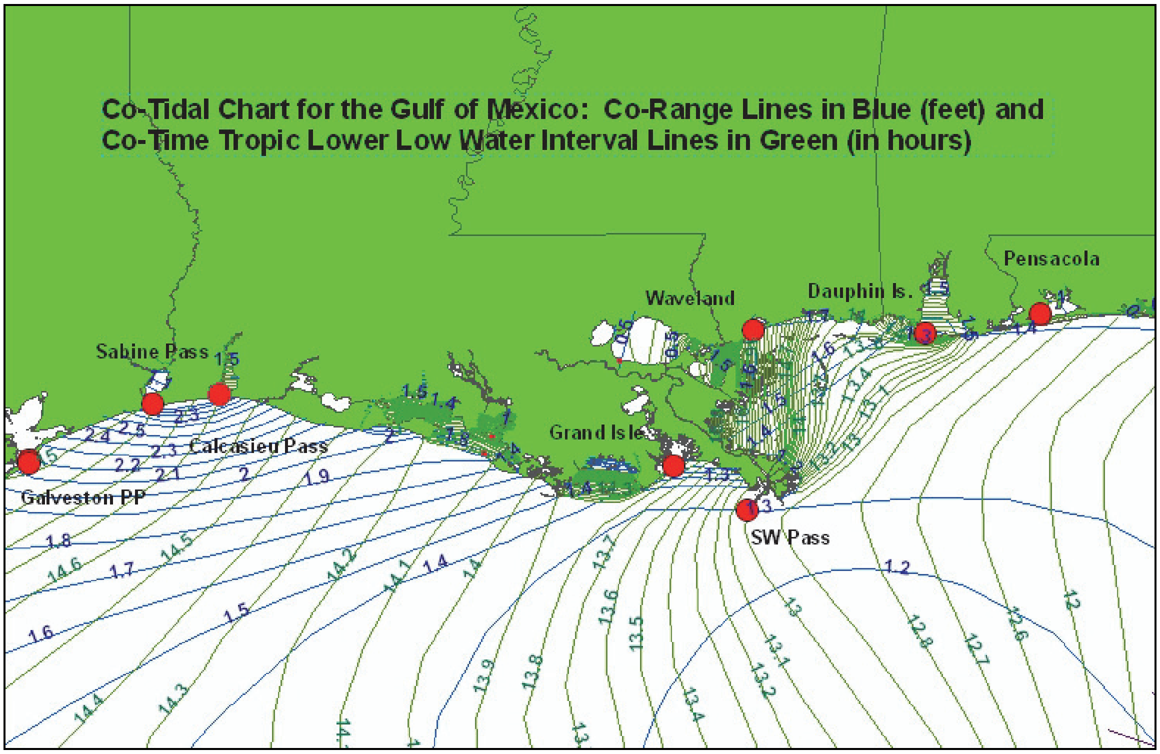

Figure 1. The cotidal lines for Diurnal Range (GT) and Tropic Lower Low Water Interval (TcLLWI) in the Gulf of Mexico

ROLE OF ERROR BUDGETS

The density of control stations in the network design is driven by error budgets of the applications. Tidal datums are local in nature and determined at specific locations by water level measurements at tide stations. Geographic extrapolation and/or interpolation of datum information from an NWLON station are constrained by errors in the technique for simultaneous comparison. These limits are driven by the tolerable uncertainties for the desired application. NOAA has traditionally used the error analysis approach in Swanson (1974) to estimate errors in tidal datums when computed at short-term stations located between NWLON stations. Errors in determination of tidal datums at short-term stations through the method of simultaneous comparison (NOS, 2003) are known to be generally correlated with geographic distance from the control station and with difference in range of tide and time of tide between control and subordinate stations (Bodnar 1981). There are other important considerations necessary for specific project implementations that are discussed later in this report in the section on limitations. Operationally for hydrographic surveys, NOAA uses the International Hydrographic Organization (IHO) error budget (see NOS Specifications and Deliverables, 2007) to construct error budget analyses for the tides component to the total error. These analyses are used to determine the number and location of subordinate stations required to obtain tide reducers for survey operations for specific areas. The error budget considers measurement error, datum computation error, and tidal zoning (extrapolation) error sub-components. Datum elevation uncertainties need to be on the order of 0.10 ft. (95% CI) for the error budget to meet known requirements. Other applications, such has shoreline surveys may have less stringent needs. The NWLON strives for the highest accuracy because of the potential multiple applications for datums at any station established by CO-OPS.

The Swanson Error Analysis Report

Swanson (1974) performed an error analysis for determining tidal datums from short-term observations. Using the comparison of simultaneous observations method, Swanson developed datum uncertainties at 1, 3, 6, and 12 month time periods based on comparisons between NWLON station pairs proceeding along the coast. One NWLON station was selected as control, the other as subordinate. The resulting datums for the shorter time periods were compared to the accepted values based on a NTDE. His analyses of these differences resulted in the generalized accuracy estimates for tidal datums determined at short-term stations for the East Coast, West Coast, and Gulf Coast (see Table 1)

Table 1. Generalized accuracy of tidal datums from short series of observation; based on one standard deviation (one-sigma) uncertainty level (from Swanson 1974).

Series Length (months)	East Coast	Gulf Coast	West Coast
1	0.13 ft.	0.18 ft.	0.13 ft.
2	0.10 ft.	0.15 ft.	0.11 ft.
3	0.07ft	0.12 ft.	0.08 ft.
4	0.05 ft.	0.09 ft.	0.06 ft.

The uncertainties of datums for Gulf Coast stations are generally higher because of the low amplitude tidal signal in that area and the relatively larger effects of weather on the water levels than the East and West Coasts. These generalized accuracy estimates have been used operationally for error budgets and error estimates for CO-OPS tidal datum products since the report was issued in 1974. It is recognized that these are regional in nature and are also expressions of maximum errors as subordinate stations are typically installed between NWLON stations, thus shortening the geographic and tidal distances between control and subordinate pairs. Because of these constraints, the Swanson regional pooled analysis does not provide a good technique for operational purposes to estimate errors at the geospatial resolution needed for precise locations of interest. The Swanson estimates cannot be easily used to describe a radius or extent of coverage of a particular NWLON station.

The Bodnar Report

In applied research performed by Bodnar (1981), multiple curvilinear regressions equations estimating the accuracy of computed datums were developed using a regression analysis of the standard deviations found in the Swanson (1974) report. Bodnar's analyses effectively determined which independent variables related to differences in tidal characteristics might explain the variations in the Swanson standard deviations using the standard deviations as the dependent variables. Table 2 summarizes the independent variables that proved to be highly significant and displays them in equation form with the slope coefficients for each variable produced by the regression model. Bodnar noted deficiencies of his approach in the sample size, interdependence of station pairs, and statistical population representation. For purposes of this study, the formulas for Mean Low Water (MLW) were adopted for use because the low water differences express the effects of shallow water and bottom friction better than Mean High Water (MHW) and the errors are more conservative (higher) than for other datums.

Table 2. The regression equations and parameters for estimating uncertainties in tidal datums for Mean Low Water (from Bodnar, 1981)

S1M = 0.0068 ADLWI + 0.0053 SRGDIST + 0.0302 MNR + 0.029

S3M = 0.0043 ADLWI + 0.0036 SRGDIST + 0.0255 MNR + 0.029

S6M = 0.0019 ADLWI + 0.0023 SRGDIST + 0.0207 MNR + 0.030

S12M = 0.0045 SRSMN + 0.128 MNR + 0.025

Where:
S is the standard deviation (in feet),
M is the number of months of subordinate station observation,
ADLWI is the absolute time difference of the Greenwich Low Water Intervals between control and subordinate stations (in hours),
SRGDIST is the square root of the geographic distance between control and subordinate stations (in nautical miles),
MNR is a mean range ratio that is defined as the absolute value of the difference in mean range between control and subordinate stations divided by the mean range of tide at the control station (using range values in feet), and
SRSMN is the square root of the sum of the mean ranges at the control and subordinate stations (in feet).

TECHNICAL APPROACH FOR DATUM COVERAGE POLYGONS

For purposes of this NWLON study, the target value of +/- 0.12 ft. (0.036m) 95% CI has been selected for determination of the extent of coverage for datum determination for each NWLON station. Even though slightly over the desired accuracy states earlier of 0.10ft, this target value is more practical and would ensure the accuracy of datum determination at subordinate locations will meet most user requirements. The study identifies the geographic region for each NWLON station within which a datum computation at a subordinate station with a 3-month time series will be accurate to less than or equal to 0.12 ft. 95% CI. Using GIS derived polygons, areas determined to contain no NWLON coverage are identified as gaps for consideration of new priority NWLON station requirements. Error analysis using a 3-month time series was selected as it is the typical length of time a subordinate station is operational for NOAA shoreline and hydrographic surveys, for outside users such as the US Army Corps of Engineers., and for VDatum model validation and error assessment.

Table 3 is an example of the error calculation for the NWLON station at Grand Isle, Louisiana. Each of the parameters required are entered into the spreadsheet for a set of stations near the location of the NWLON station. They are obtained from the CO-OPS GIS historical tide station data table, which also provides latitude and longitude information. The historical station table has been populated in support of using GIS tools for tidal zoning and reflects the most recent record of operational and historic water level stations. The information includes station location, time period of measurement, Greenwich and Tropic Interval values, and Mean and Diurnal range of tide values. Geographic distance is estimated within ArcGIS using the GIS measure tool.

The basic equation being used in the spreadsheet calculation is:

1) $S3M = 0.0043\ ADLWI + 0.0036\ SRGDIST + 0.0255\ MNR + 0.029.$

Equation 1 shows that the error in a datum computation at a 3-month long subordinate station is dependent upon the difference in time of low waters between control and subordinate (first term), geographic distance from the control to the subordinate (second term), and ratio of the mean ranges of tide (third term) (see table 2). The values of the coefficients for each term show the relative weight of each of the terms. The coefficients for time difference and geographic distance are about the same and both are much less that the coefficient for the range ratio term. Thus differences in range of tide between control and subordinate contribute more to the error than time difference or geographic distance. The last term in equation 1 is a constant of 0.029 ft. It represents the error in the datum because the time series at the subordinate is only 3-months long instead of 19-years. It is the remaining error if the difference in time of low waters was zero and the subordinate station was co-located with the control station.

For tide stations at the tides are predominantly diurnal (one high tide and one low tide per day), alternate procedures for determining time differences are used. Values for Greenwich high and low water intervals are only computed when there are two high and two low waters each tidal day, and are therefore not computed for diurnal stations. A substitute for difference in time of tide is derived from the difference in tropic time intervals (TcLLWI) derived from harmonic analyses at each of the stations. The values for diurnal range of tide (GT) are used as a substitute for mean range of tide (MN) in the Gulf as well because GT is a much better technical description of the full daily range of tide for diurnal tides. These values are readily available from the CO-OPS historical tide station GIS table as these values are used for tidal zoning and planning tide support for hydrographic and shoreline surveys. Regions of the Gulf of Mexico are examples where diurnal tides are found.

Figure 4 is a map showing the location of the NWLON station at Grand Isle, LA, the locations of historical stations used in the datum error analyses, and the locations of the stations for which the error equation results in a value of <=0.06 ft.(one standard deviation) or <= 0.12 ft. 95% confidence level. Offshore data points are located at the intersection of the co-range and co-time lines, thus providing data values and a distance to be entered into the Bodnar equation spreadsheet (Table 3). Co-range lines (GT) are shown in blue and co-time lines (TcLLWI) are shown in green. The estimated error column in Table 3 (labeled S3M) is at the one standard deviation which converts to a 95% CI by multiplying by 1.96,

Figure 5 is a GIS polygon drawn using the data points in Figure 4 as a guide. This polygon is the estimated spatial representation of datum coverage for Grand Isle, LA for datum computation at nearby subordinate stations. Grand Isle would provide less accurate control for datum determination for stations outside this polygon, unless the subordinate stations were left in for one-year or longer. The polygon was manually constructed using a GIS drawing tool and visual interpolation between the numerical value of the error assigned to each location.

Table 3. An example of a Bodnar Equation error analysis spreadsheet for a three-month datum comparison using Grand Isle, LA as control.

Grand Isle Control Accepted Values			TCLLWI	14.327 hrs.	GT	1.06 ft.			
	TCLLWI	ADLWI	DIST	SQRDIST	Sub. Range	MNR	S3M		
		hrs.	n. miles			ratio	ft.	LAT	LONG
Southwest Pass	13.16	1.17	35.30	5.94	1.30	0.23	0.061	28.93	-89.42
Pelican Island	14.30	0.03	19.00	4.36	1.12	0.06	0.046	29.27	-89.60
Caminada Pass	14.54	0.21	6.33	2.52	0.99	0.07	0.041	29.21	-90.04
Mendicant Island	15.57	1.24	3.80	1.95	1.00	0.06	0.043	29.32	-89.98
Billet Bay	16.33	2.00	12.60	3.55	1.02	0.04	0.051	29.37	-89.75
Hackberry Bay	16.49	2.16	9.20	3.03	0.90	0.15	0.053	29.41	-90.04
St Marys Point	15.94	1.61	10.20	3.19	1.00	0.06	0.049	29.43	-89.93
Bay Rambo	18.37	4.04	11.30	3.36	0.73	0.31	0.066	29.36	-90.15
Bayou St. Dennis	19.98	5.65	14.50	3.81	0.80	0.25	0.073	29.50	-90.02
Port Fourchon	14.32	0.01	16.30	4.04	1.26	0.19	0.048	29.12	-90.21
Shell Oil, East Bay	13.64	0.69	36.40	6.03	1.32	0.25	0.060	29.06	-89.04
East Timbalier Is.	15.20	0.87	20.90	4.57	1.33	0.25	0.056	29.08	-90.29

(Table 3 continued)

		TCLLWI	ADLWI hrs.	DIST n. miles	SQRDIST	Sub. Range	MNR ratio	S3M ft.	LAT	LONG
Leeville		17.31	2.98	13.80	3.71	0.88	0.17	0.060	29.56	-90.21
Golden Meadow		21.05	6.72	17.60	4.20	0.56	0.47	0.085	29.38	-90.27
Bayou Petit Caillou		15.21	0.88	37.50	6.12	1.29	0.22	0.060	29.19	-90.66
Cocodrie		16.05	1.72	36.80	6.07	1.05	0.01	0.058	29.24	-90.66
Four Island Bayou		17.90	3.57	43.10	6.57	1.06	0.00	0.068	29.24	-90.78
Bayou Dulac		19.58	5.25	39.60	6.29	0.38	0.64	0.091	29.46	-89.79
Pointe Au Chien		19.38	5.05	26.80	5.18	0.45	0.58	0.084	29.42	-90.45
South Pass		12.91	1.42	45.60	6.75	1.22	0.15	0.063	28.99	-89.14
Pilot Town		15.13	0.80	38.10	6.17	1.00	0.06	0.056	29.18	-89.26
Venice		21.50	7.17	31.90	5.65	0.98	0.08	0.082	29.27	-89.36
North Pass		13.58	0.75	47.70	6.91	1.10	0.04	0.058	29.21	-89.04
Offshore Point 1		13.80	0.53	12.00	3.46	1.40	0.32	0.052	29.10	-90.10
	2	13.90	0.43	34.20	5.85	1.40	0.32	0.060	29.00	-90.53
	3	13.90	0.43	56.20	7.50	1.40	0.32	0.066	28.83	-90.91
	4	13.70	0.63	23.30	4.83	1.30	0.23	0.055	28.93	-90.20
	5	13.50	0.83	19.30	4.39	1.30	0.23	0.054	28.94	-89.91
	6	13.20	1.13	26.80	5.18	1.30	0.23	0.058	28.94	-89.60
	7	13.10	1.23	68.40	8.27	1.20	0.13	0.067	28.24	-89.40
	8	13.90	0.43	48.60	6.97	1.50	0.42	0.067	29.02	-90.85

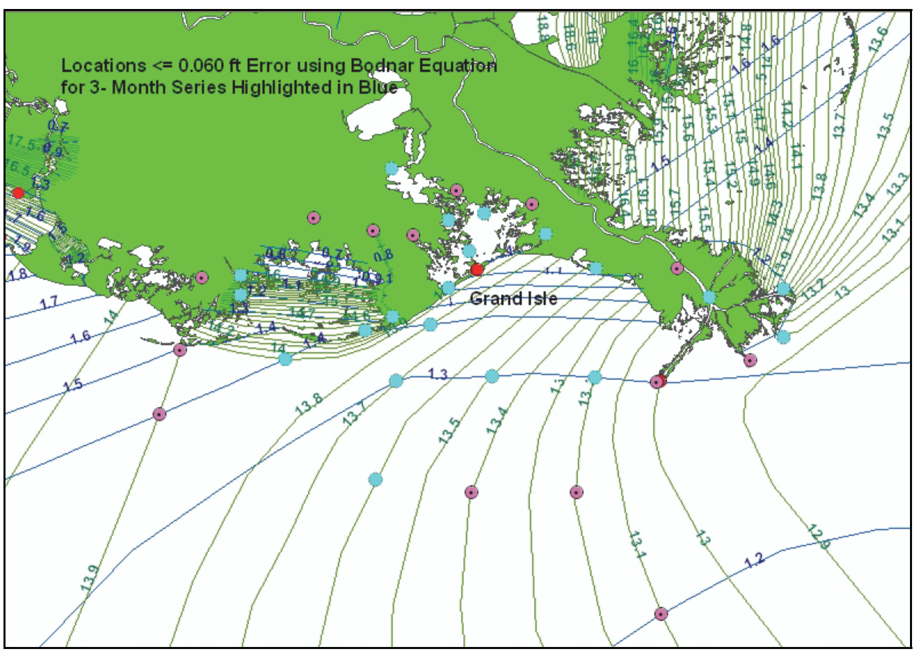

Figure 2. The locations of historical tide stations and offshore points used in the Bodnar equation for Grand Isle with locations within the 0.060 ft. cutoff highlighted in blue.

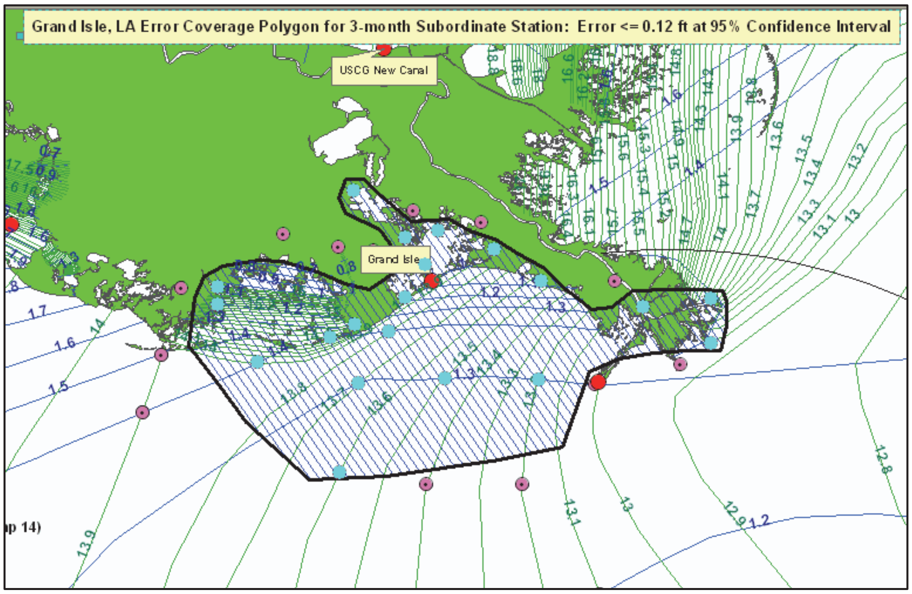

Figure 3. The GIS error polygon for Grand Isle depicting the geographic area of coverage for datum determination at subordinate stations.

Figure 4 below shows the polygon analysis for other stations in the region near Grand Isle. The overlap and the lack of overlap in coverage polygons are readily apparent. This analysis has been repeated around the U.S. coastline, excluding the remote Pacific Ocean islands and the U.S. Great Lakes.

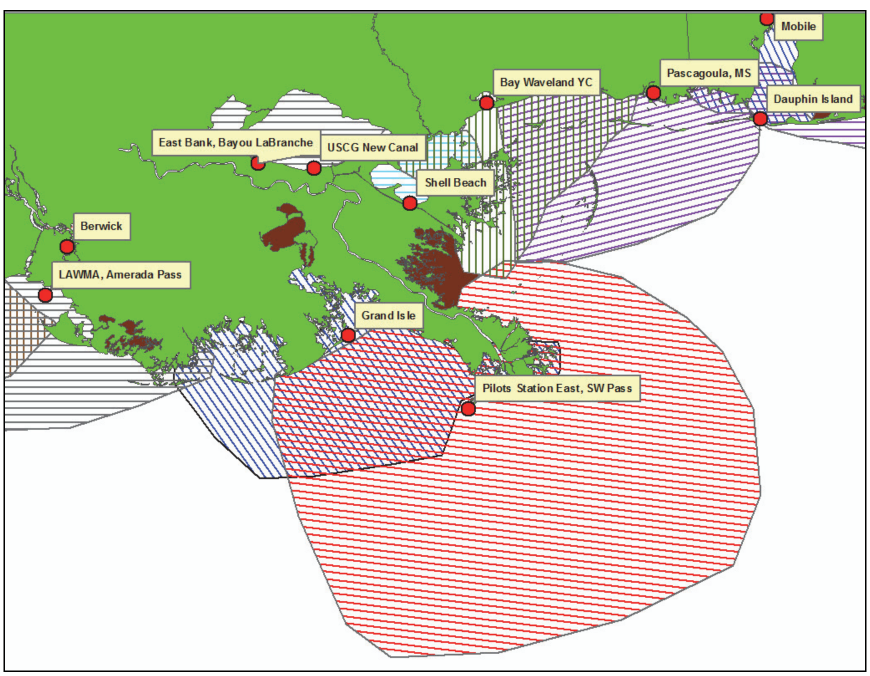

Figure 4. Example of the GIS analysis results for Grand Isle, LA and nearby NWLON stations.

THE NWLON COVERAGE POLYGON RESULTS

East Coast

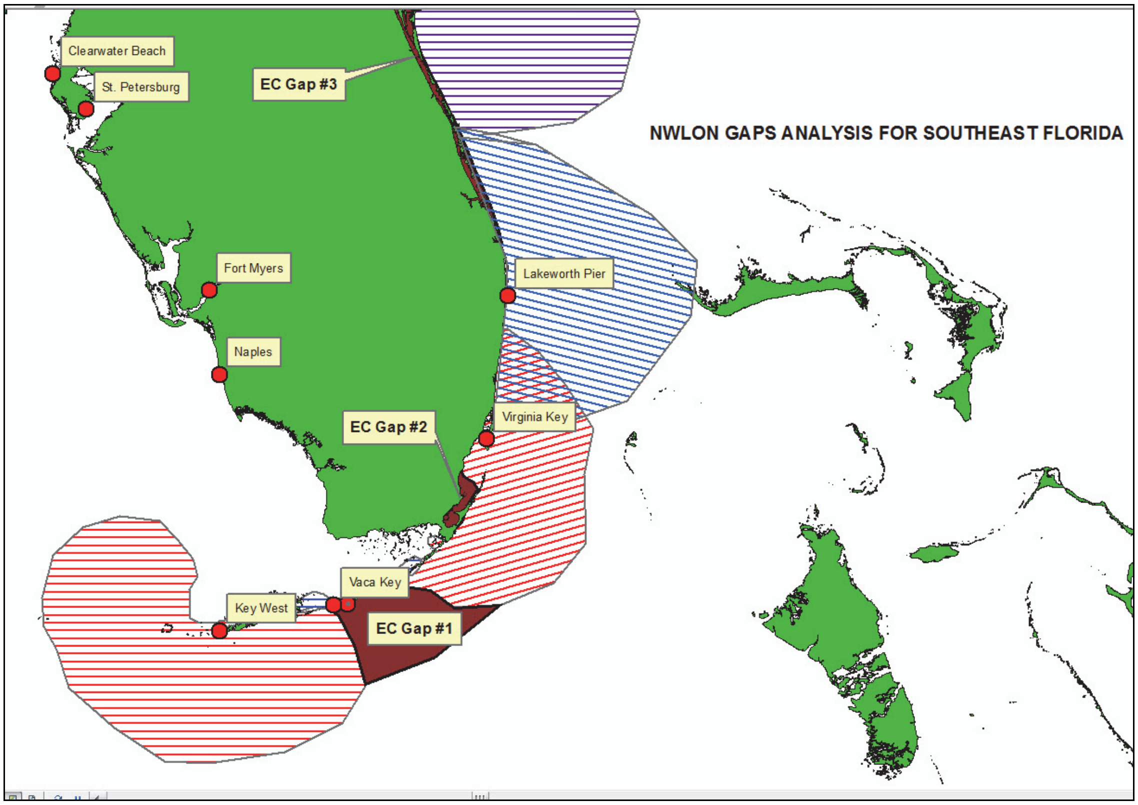

Figure 5. NWLON gaps analysis for southeast Florida

1) Ocean Coast Key Colony Beach
2) Southern Biscayne Bay
3) Inner Bays, Indian River, FL: This is an area of transition from tidal on the outer coast to non-tidal in the inner bays.

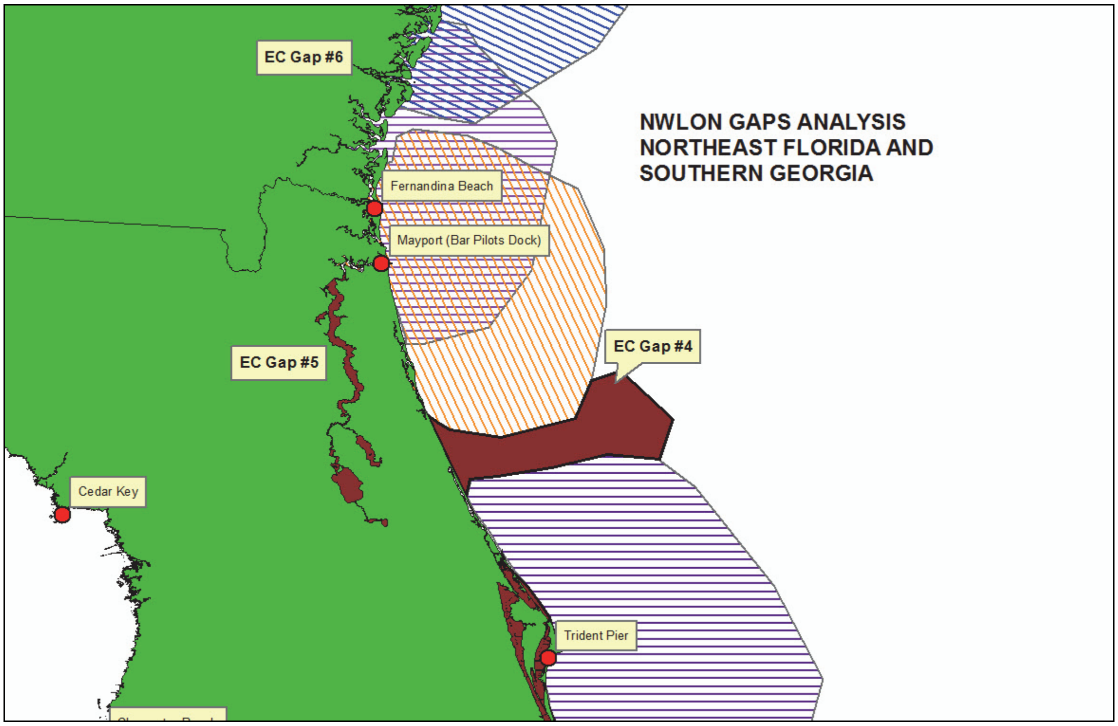

Figure 6. NWLON gaps analysis for northeast Florida and southern Georgia

4) Outer Coast, Vicinity of Flagler Beach, FL: The former NWLON station at St. Augustine Beach filled this gap, but the pier no longer extends to deep water due to beach re-nourishment.
5) Upper St. Johns River, FL**
6) Upper Satilla River, GA

** - newly installed Jacksonville PORTS® partnership tide stations may eventually help fill this gap

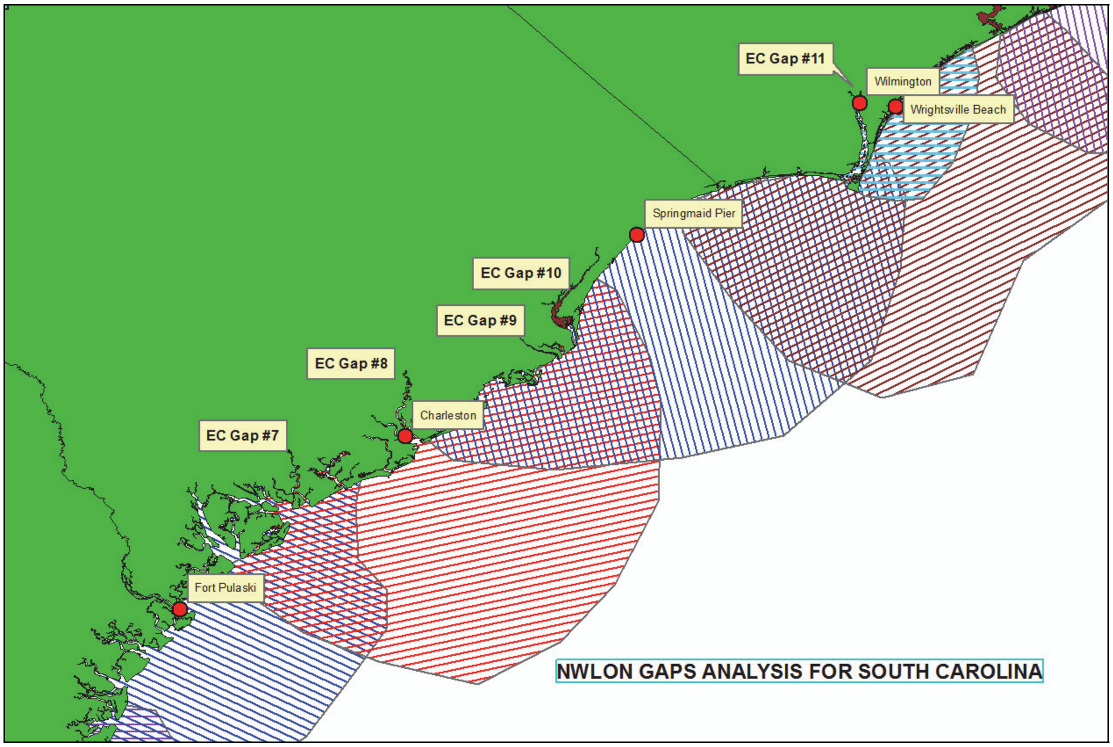

Figure 7. NWLON gaps analysis for South Carolina

7) Upper Edisto River, SC
8) Upper Cooper River, SC
9) South Santee River, SC
10) Winyah Bay, SC
11) Upper Cape Fear River, NC

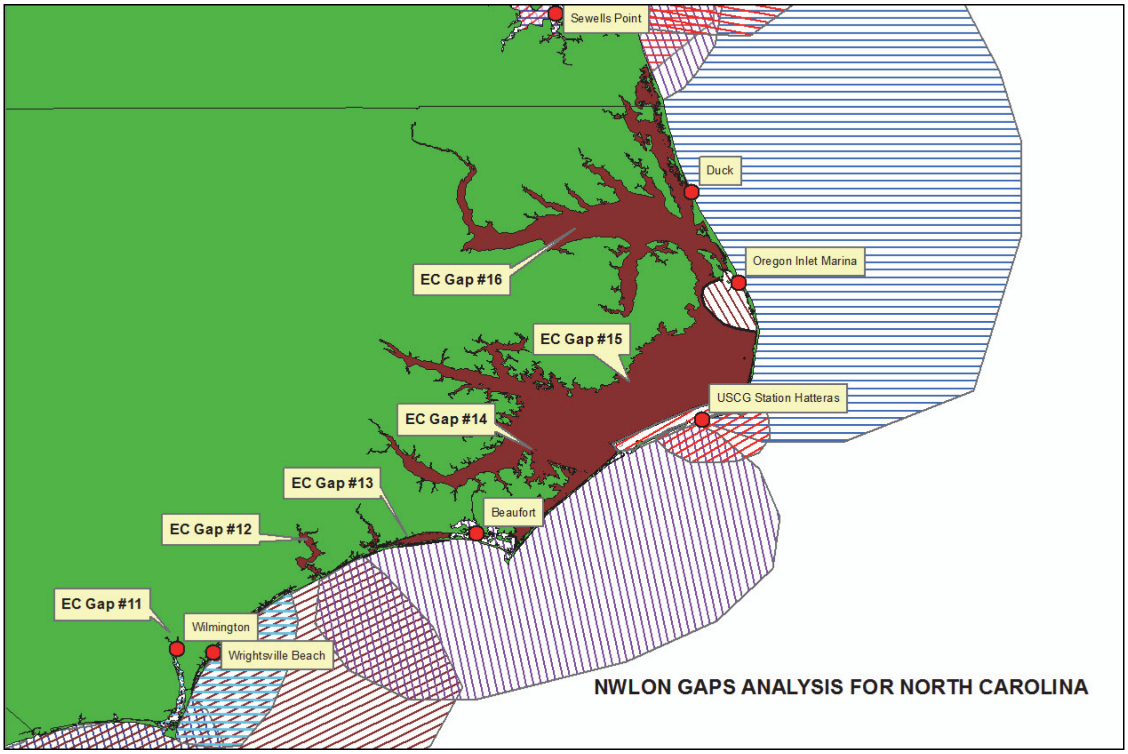

Figure 8. NWLON gaps analysis for North Carolina

12) New River, NC
13) Bogue Inlet/Sound, NC
14) Cedar Island, Southern Pamlico Sound, NC
15) Western Pamlico Sound, NC
16) Albemarle Sound, NC

Note that for gap areas 12 through 15 represent areas of transition from tidal on the outer coast to non-tidal in the inner bays.

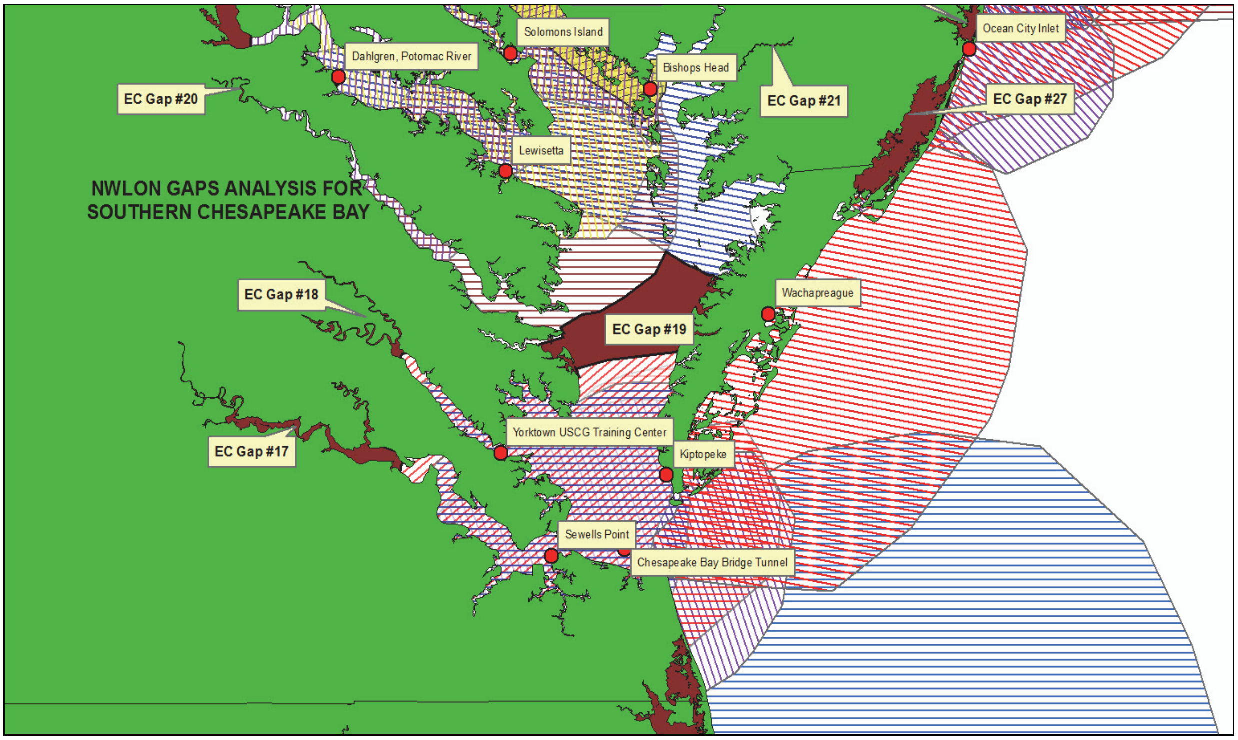

Figure 9. NWLON gaps analysis for the southern Chesapeake Bay

17) Upper James River, VA
18) Upper York River, VA
19) Lower Chesapeake Bay Vicinity of Rappahannock Shoal, VA**
20) Upper Rappahannock River, VA
21) Upper Wicomico River, MD

** The existing long-term PORTS partnership station at Windmill Point may eventually fill this gap

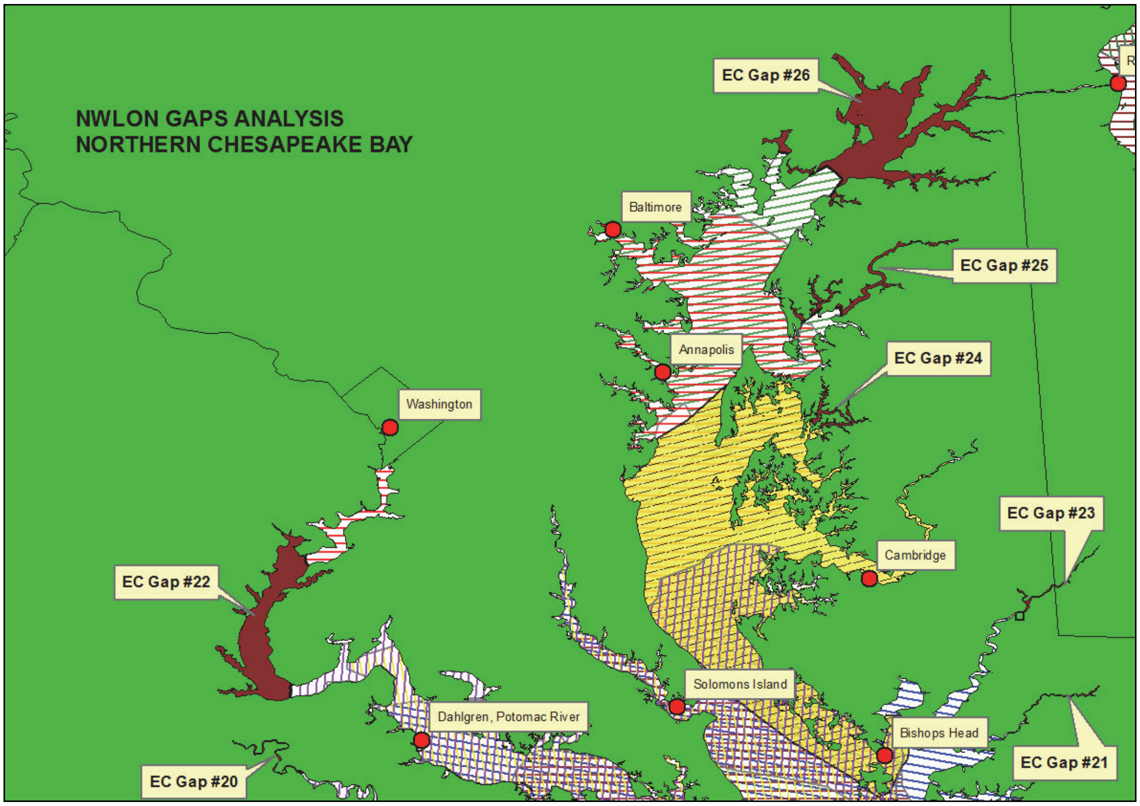

Figure 10. NWLON gaps analysis for the northern Chesapeake Bay

22) Potomac River, MD/VA
23) Upper Nanticoke River, MD
24) Vicinity of Wye River, Eastern Bay, MD
25) Upper Chester River, MD
26) Havre de Grace, Upper Chesapeake Bay, MD**

Note gaps are generally at the upper ends of the tidal rivers in this region.

** This gap may eventually be filled by the long-term Chesapeake Bay PORTS® partnership station at Tolchester Beach.

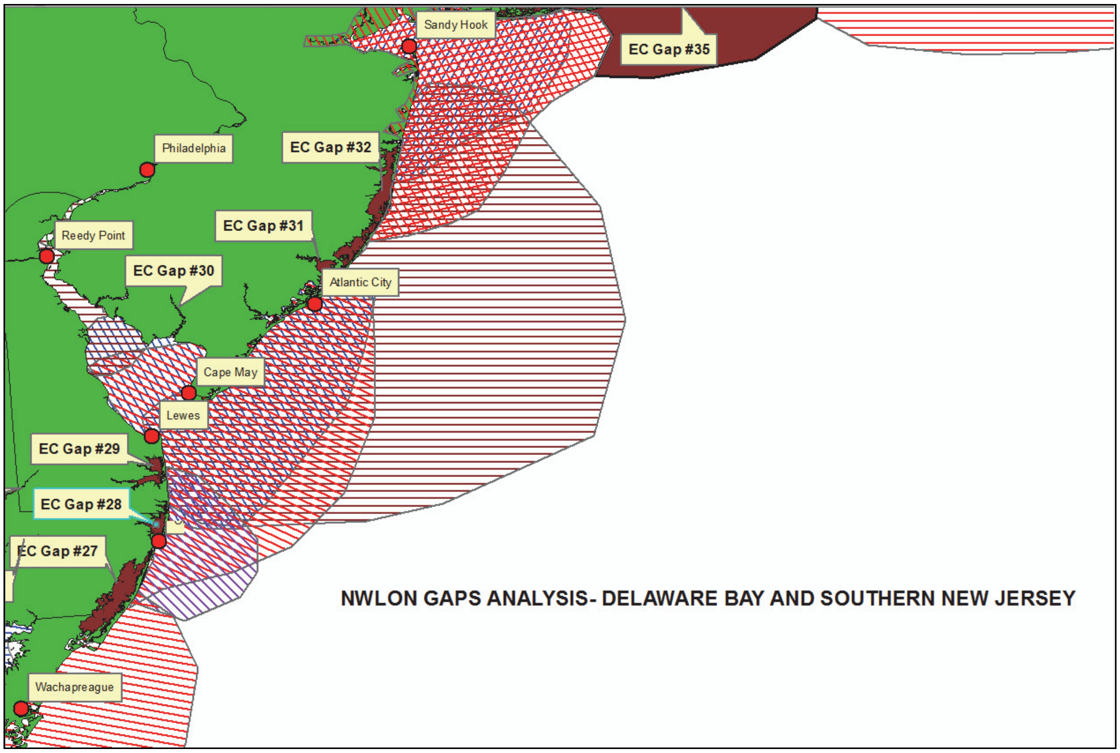

Figure 11. NWLON gaps analysis for Delaware Bay and southern New Jersey

27) Chincoteague Bay, MD
28) Isle of Wight and Assawoman Bays, MD
29) Indian River, DE
30) Maurice River, NJ
31) Great Egg Harbor, NJ
32) Barnegat Bay, NJ

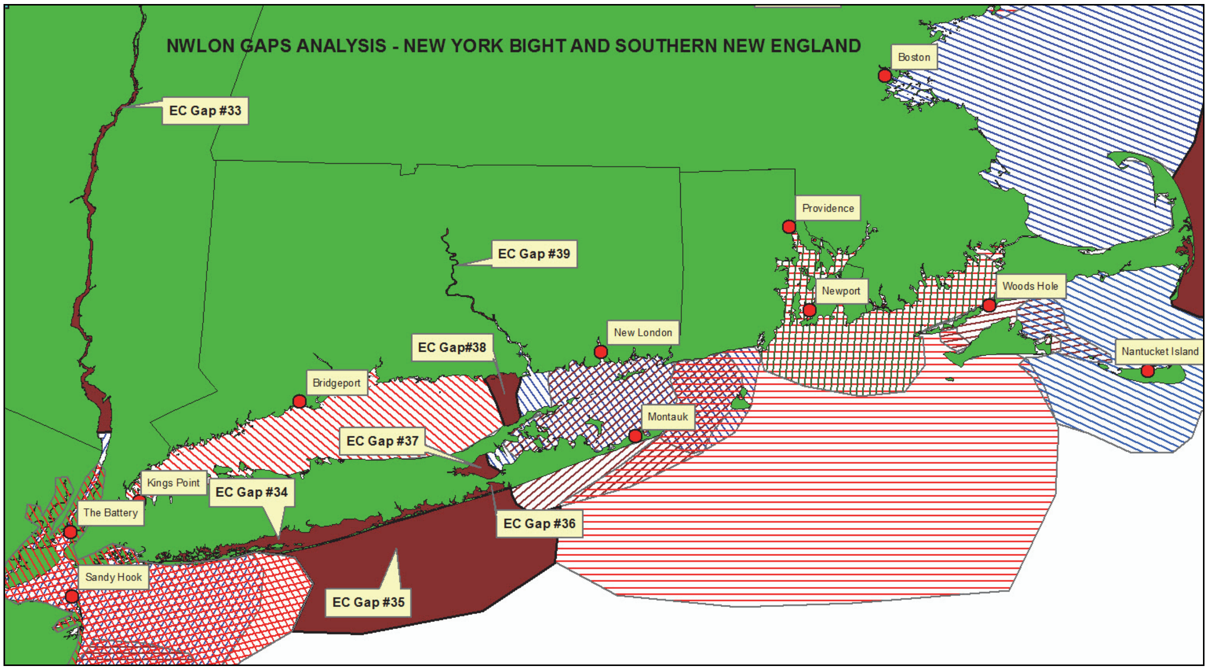

Figure 12. NWLON gaps analysis for New York and southern New England

33) Mid-Hudson River, NY
34) Great South Bay, NY
35) Southern Shore, Outer Coast, Long Island
36) Inside Shinnecock/Moriches Bay, NY
37) Western Peconic Bays, NY
38) Eastern Long Island Sound, CT/NY **
39) Upper Connecticut River, CT

Note: ** This gap is presently being operationally filled by a long-term PORTS® partnership station at New Haven

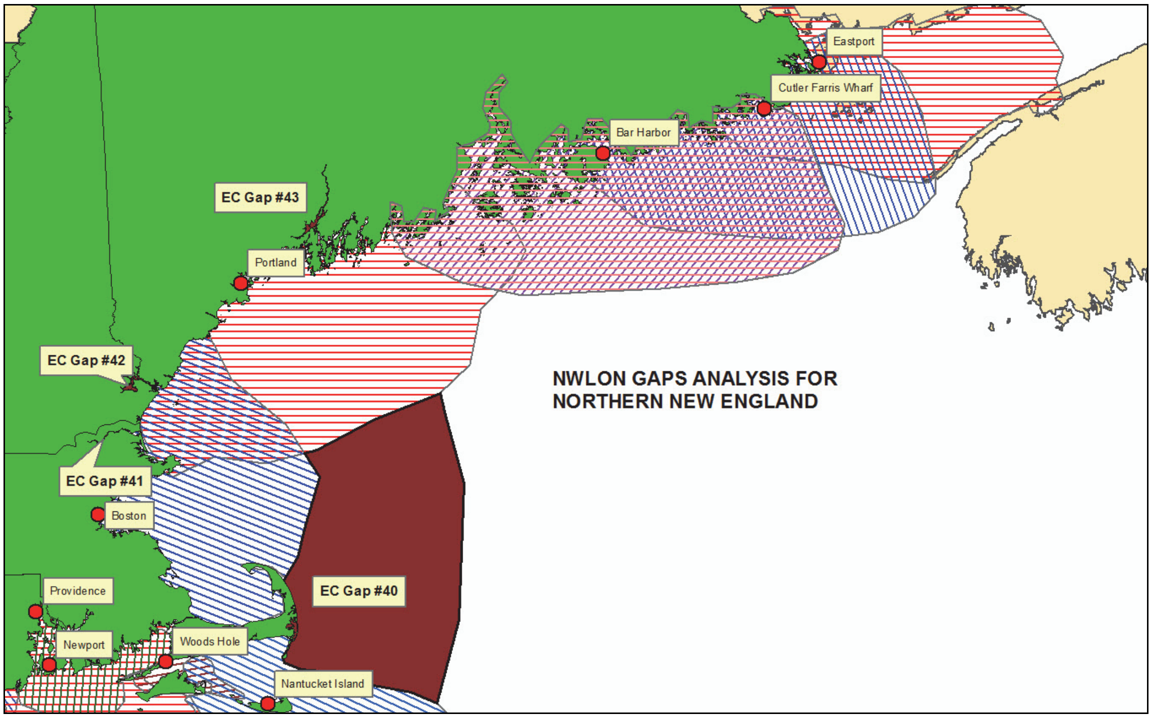

Figure 13. NWLON gaps analysis for northern New England

40) Outer Cape Cod coast **
41) Upper Merrimack River
42) Vicinity of Bellamy River, NH
43) Upper Kennebec River, ME

** This gap is operationally being filled with a long-term partnership station operating at Chatham Harbor.

Caribbean

The gaps analysis for the Caribbean (Figure 14) shows that with the addition of the recent NWLON stations established as part of the tsunami warning system upgrade in the region, there are no gaps in NWLON coverage for Puerto Rico and the U.S. Virgin islands. The addition of the new NWLON stations established through the tsunami warning system upgrade results in several layers of redundancy in coverage for tidal datum purposes in the Virgin Island region.

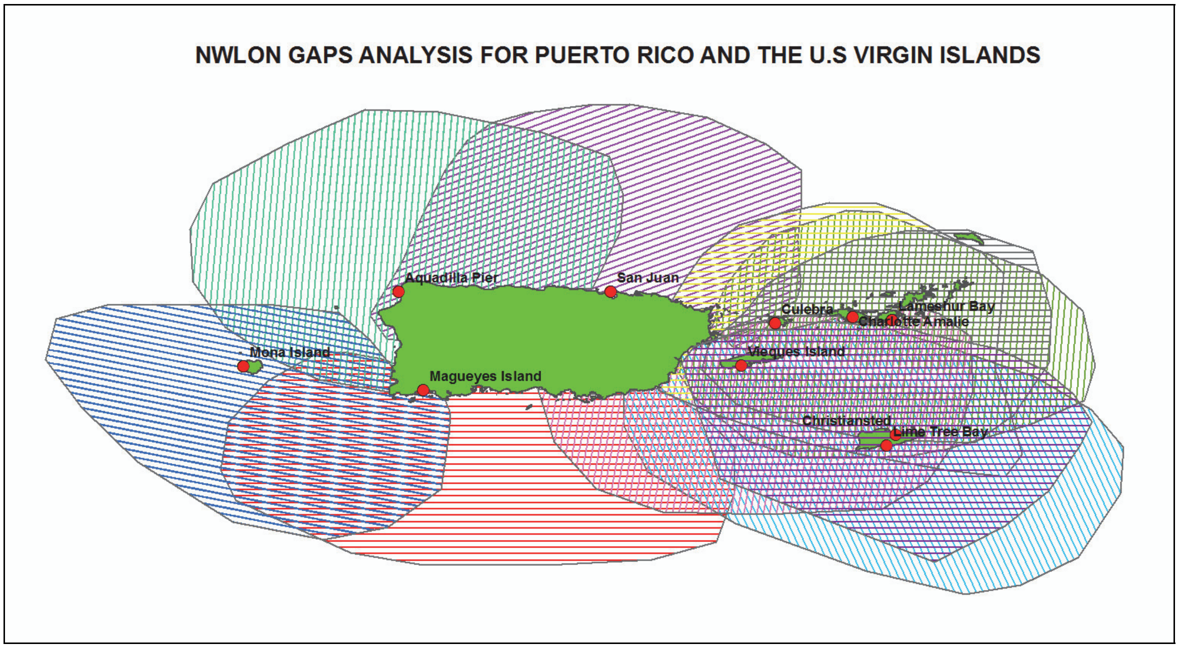

Figure 14. NWLON gaps analysis for the Caribbean exhibiting no existing gaps in coverage

Gulf Coast

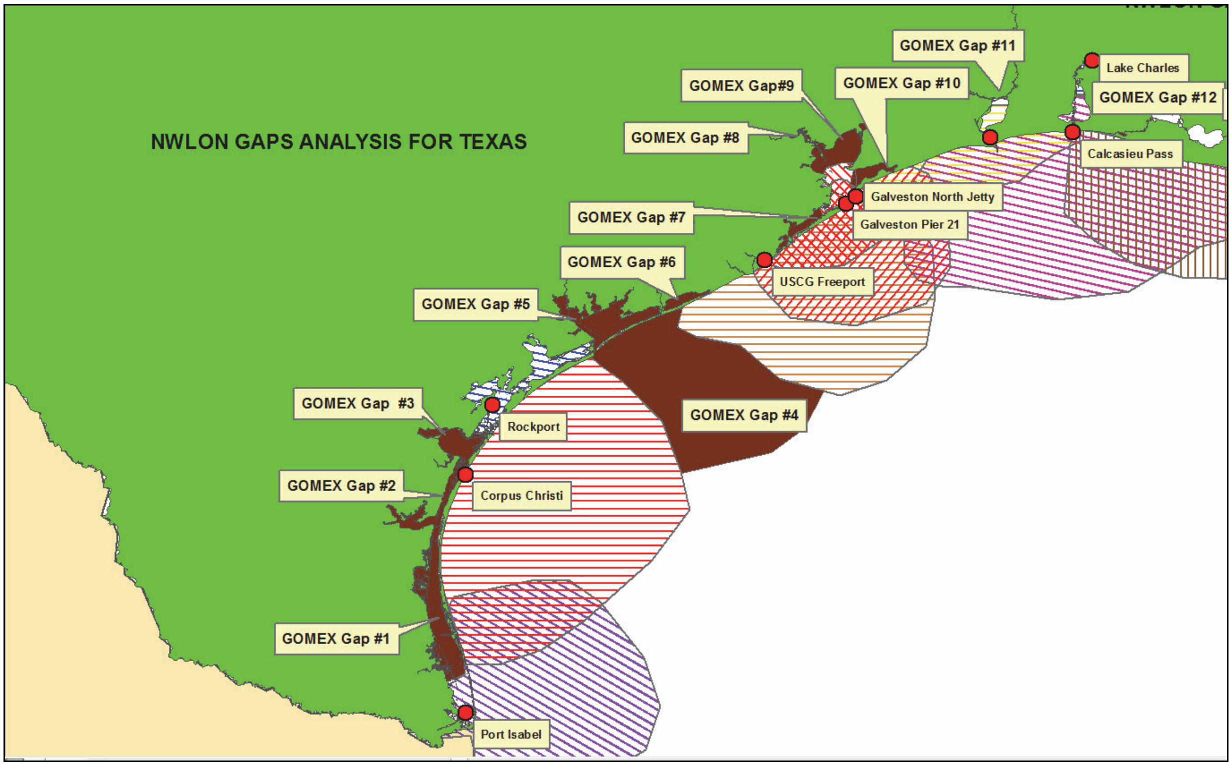

Figure 15. NWLON gaps analysis for Texas

1) Southern Laguna Madre, TX: This is an area of transition from tidal on the outer coast to non-tidal in the inner bays. **
2) Northern Laguna Madre, TX: This is an area of transition from tidal on the outer coast to non-tidal in the inner bays. **
3) Corpus Christi Bay; Aransas Pass Inside, TX**
4) Outer Coast, Pass Cavallo **
5) Lavaca, Keller, Carancahua, Tres Palacios Bays, TX**
6) Matagorda, East Matagorda Bays, TX **
7) West Bay,TX **
8) Houston Ship Channel, TX: This is an area with high rates of land subsidence. **
9) Upper Galveston Bay, TX **
10) East Bay, TX **
11) Upper Neches and Sabine Rivers, TX/LA **

**** -** These gaps are presently being operationally filled with the partnership with Conrad Blucher Institute Texas Coastal Ocean Observing Network (CBI, 2014) and the Houston Galveston PORTS® stations

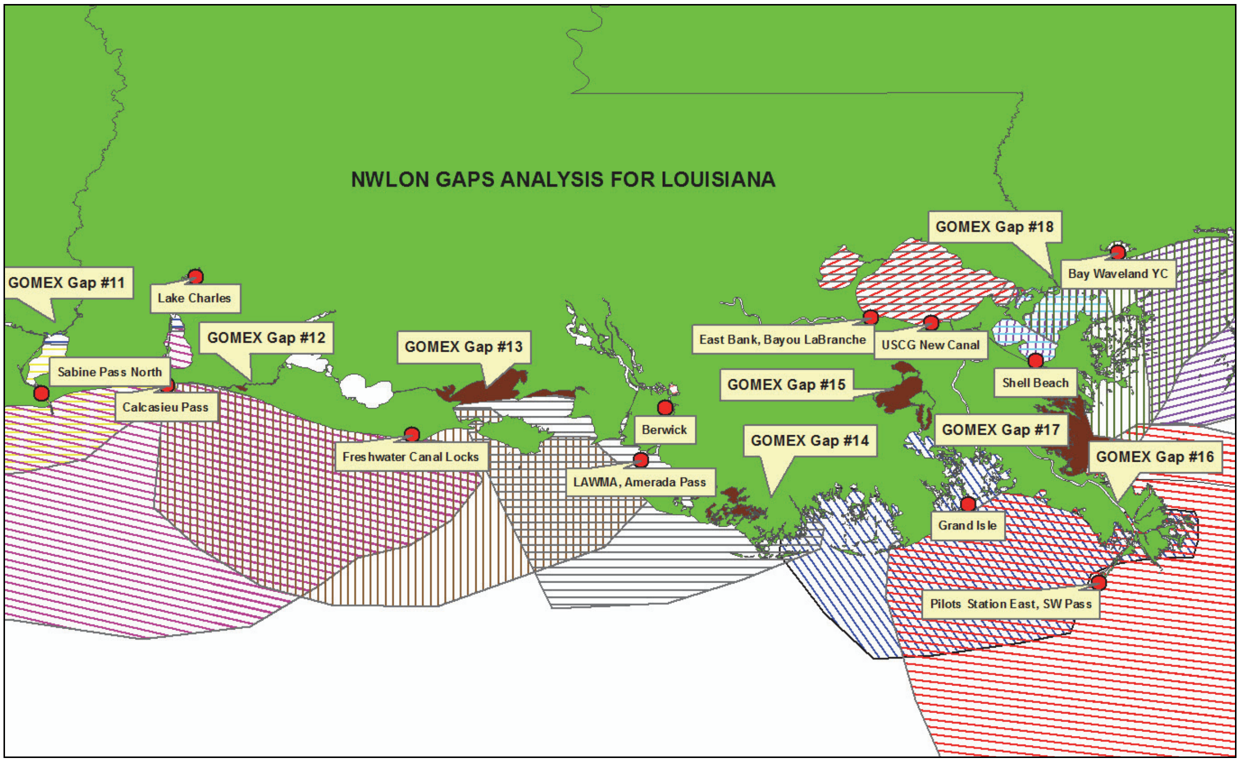

Figure 16. NWLON gaps analysis for Louisiana

12) Lower and Upper Mud Lake Vicinity
13) Upper Vermillion and West Cote Blanche Bays, LA
14) Houma Ship Canal, LA
15) Lake Salvador : This is an area of transition of tidal to non-tidal. **
16) Lower Mississippi River, LA: The river transitions from tidal to non-tidal in this region.
17) Breton Sound, LA
18) Lower Pearl River, LA/MS

** This gap is presently being operationally filled with a long-term partnership station at West Bank, Bayou Gauche

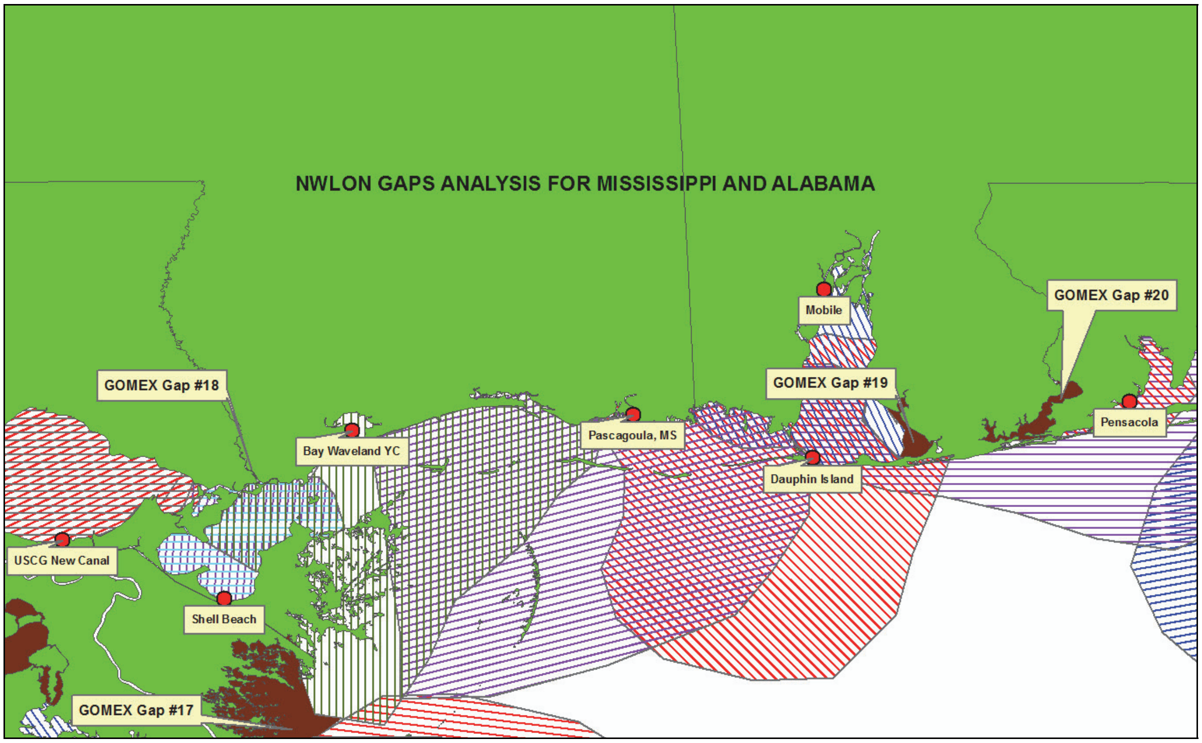

Figure 17. NWLON gaps analysis for Mississippi and Alabama

19) Weeks Bay, AL**
20) Wolf Bay, AL and Perdido Bay, AL/FL

** This gap is presently being operationally filled with a long-term partnership station at Weeks Bay National Estuarine Research Reserve .

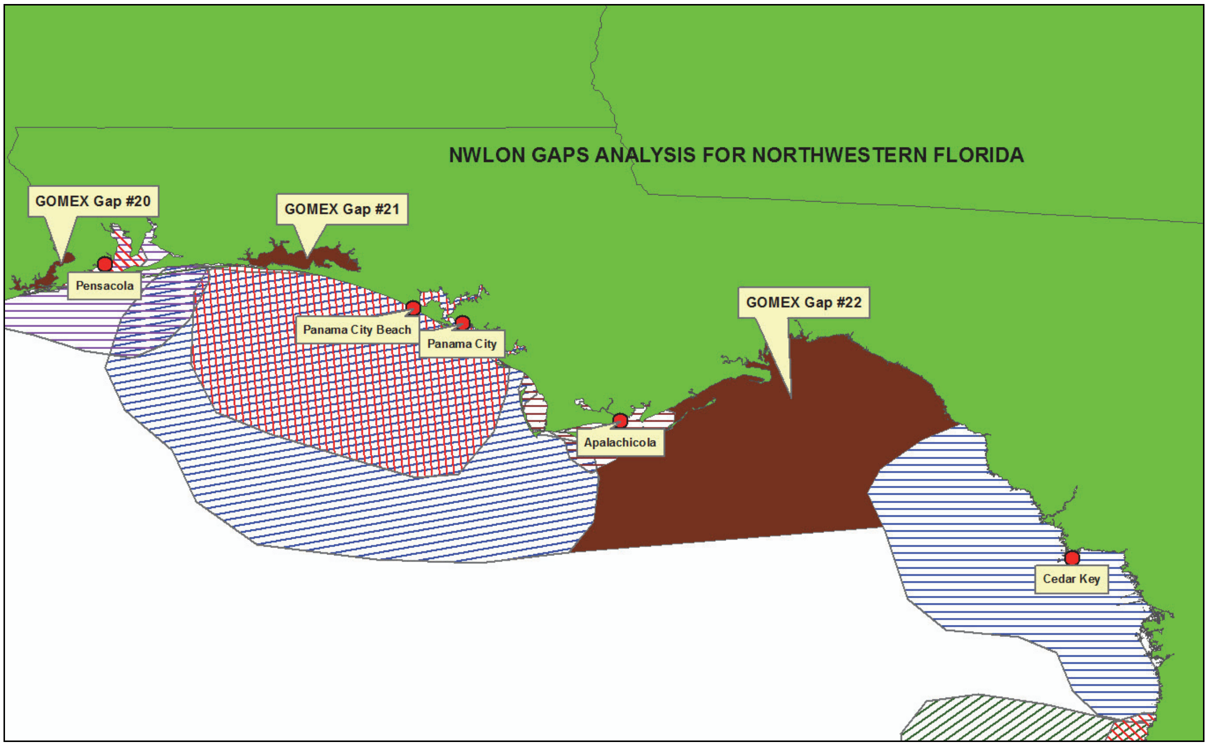

Figure 18. NWLON gaps analysis for northwest Florida

21) Choctawhatchee Bay, FL
22) Apalachee Bay, St. George Sound, FL and Vicinity

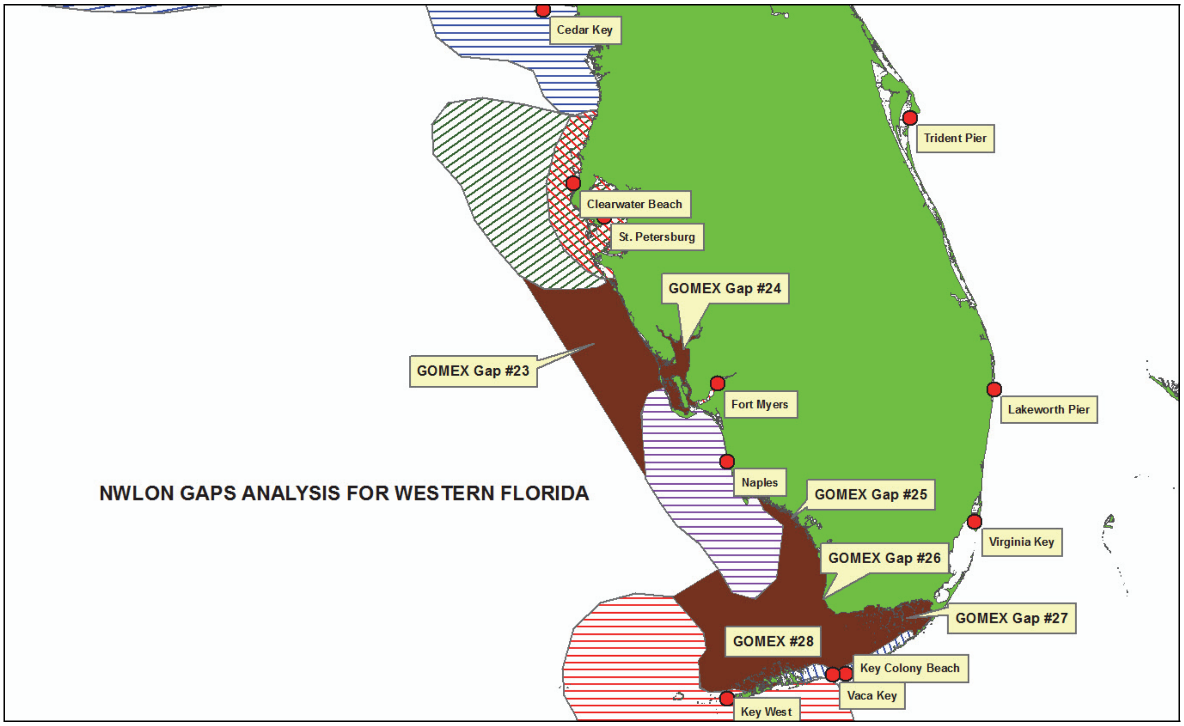

Figure 19. NWLON gaps analysis for southwest Florida

23) Vicinity and Outer Coast of Venice, FL
24) Charlotte Harbor, FL
25) Chokoloskee, FL
26) Cape Sable, FL
27) Northern Florida Bay, FL: This bay is a region of transition from tidal to non-tidal.
28) Lower Keys (Gulf of Mexico side) and Vicinity, FL

West Coast

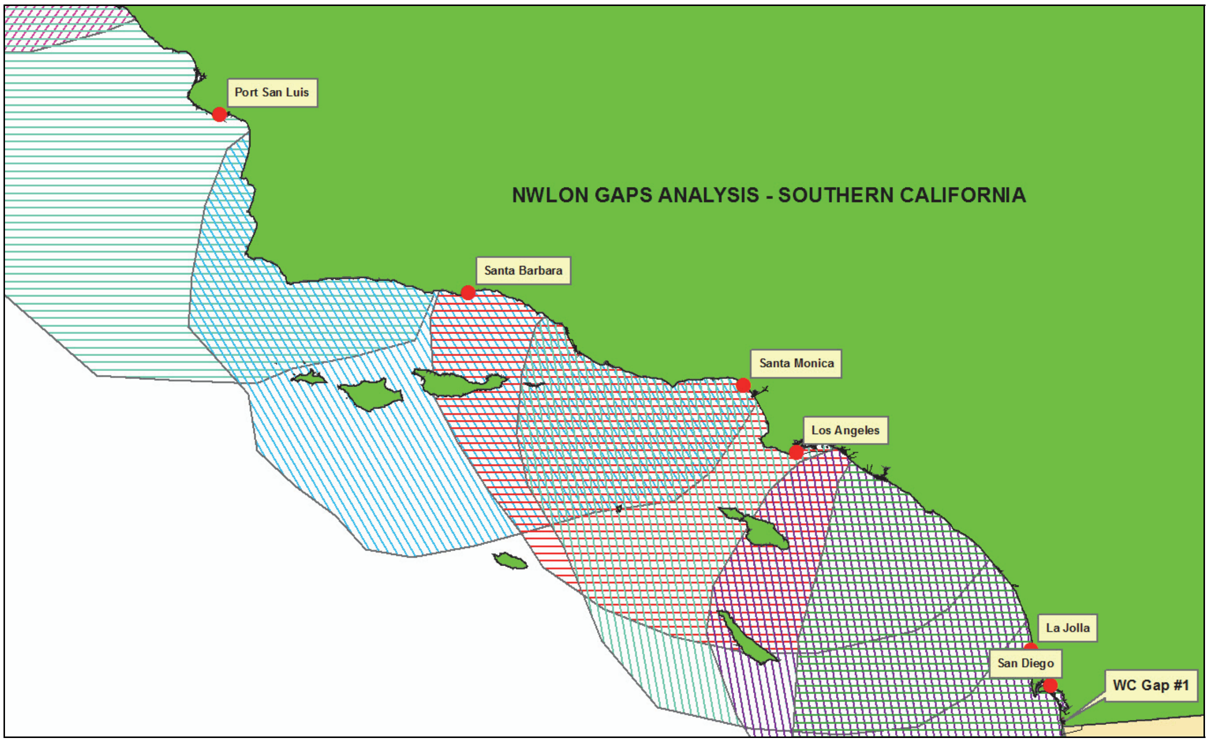

Figure 20. NWLON gaps analysis for southern California

1) Tijuana Slough, CA

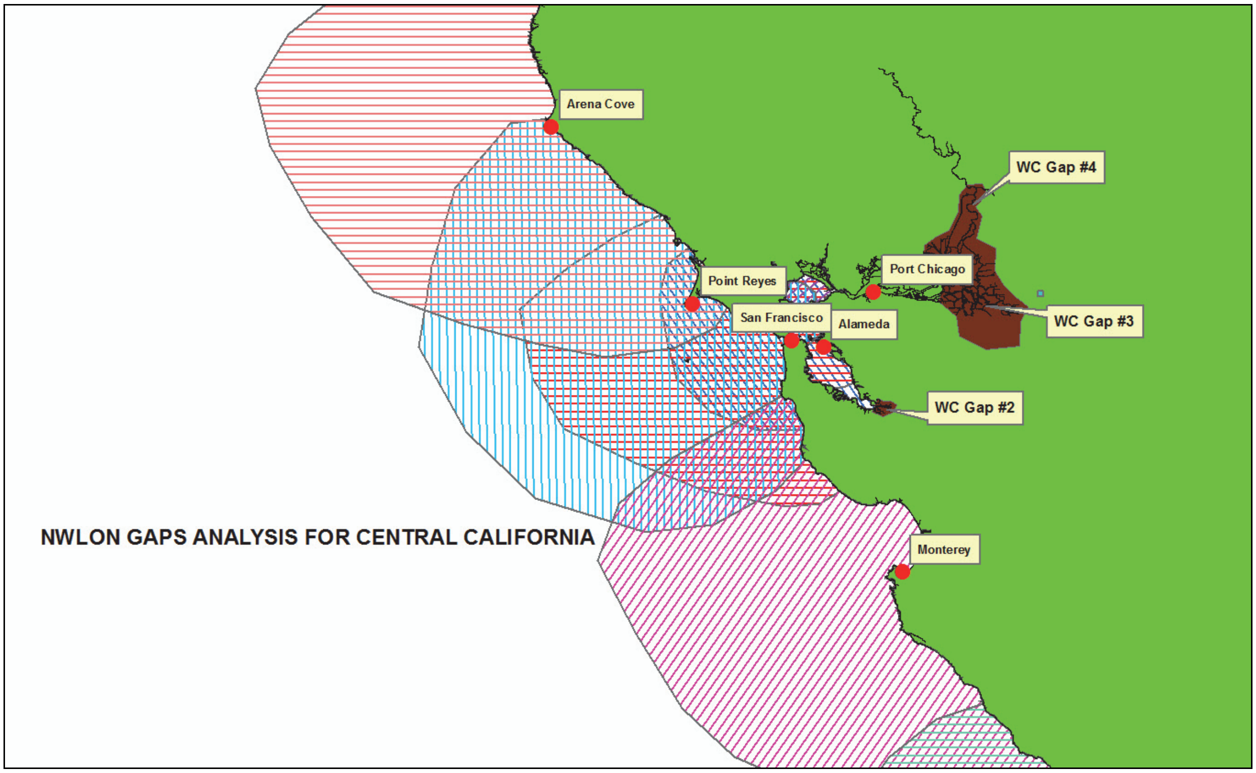

Figure 21. NWLON gaps analysis for central California

2) South San Francisco Bay, CA**
3) Stockton River Delta, CA
4) Sacramento River Delta, CA: This portion of the river transitions from tidal to non-tidal.

Note: The Lower Sacramento River Delta and the Stockton River Delta, CA are both areas of land subsidence.
** This gap is being operationally filled with the San Francisco PORTS® station at Redwood City. The new long-term partnership station at Coyote Creek could eventually fill this gap if Redwood City were removed.

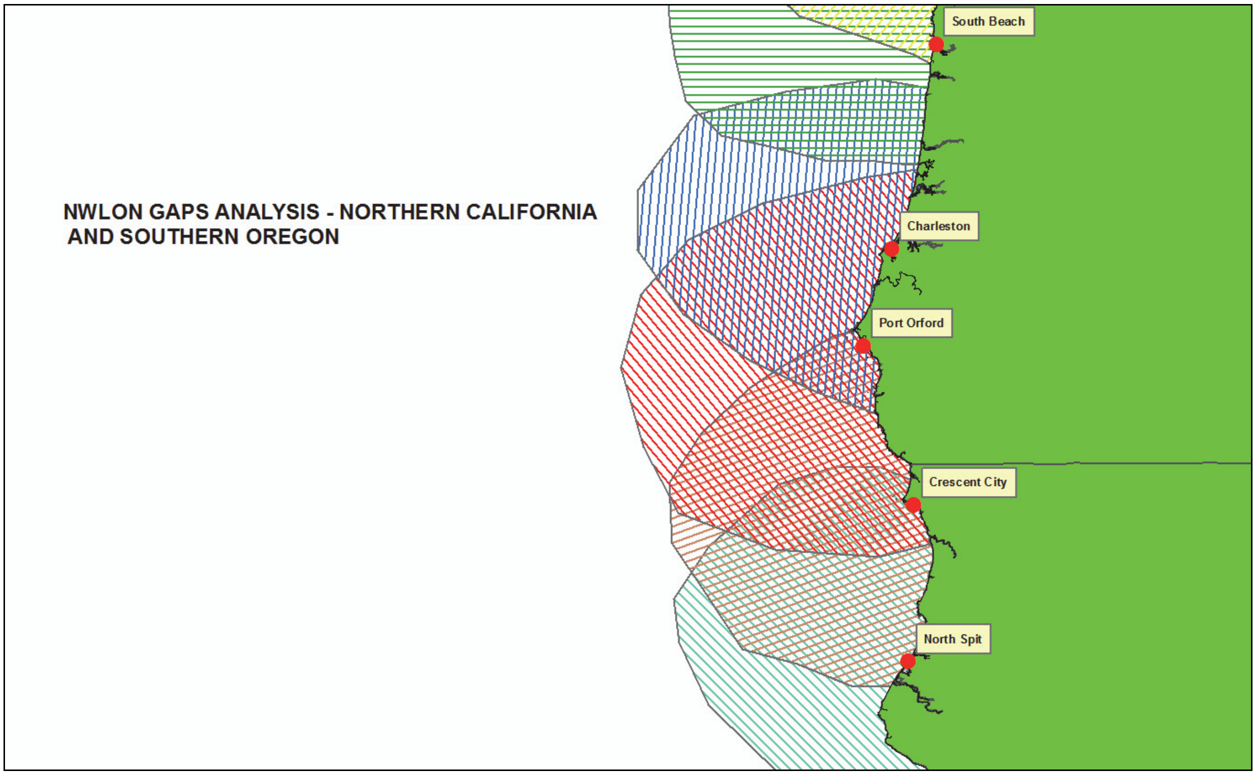

Figure 22. NWLON gaps analysis for northern California and southern Oregon

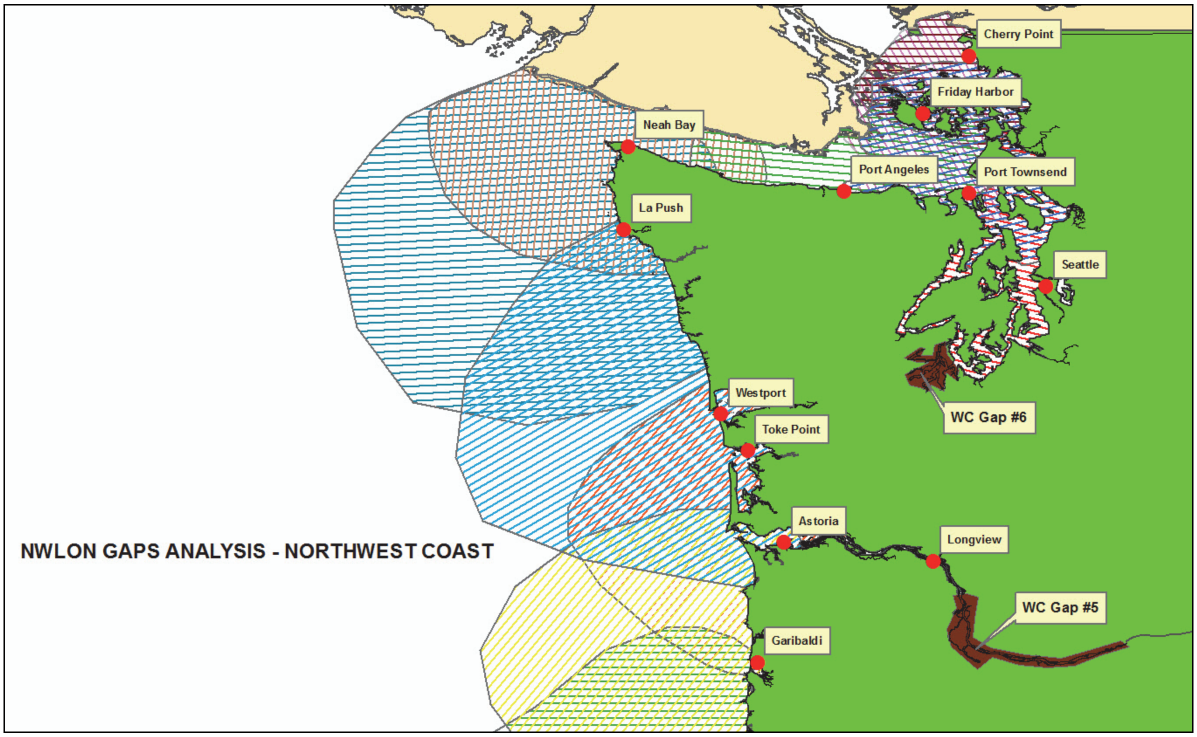

Figure 23. NWLON gaps analysis for the northwest coast and Puget Sound

5) Upper Columbia River, OR/WA **
6) Olympia, Budd Inlet, WA

Note: The upper Columbia River uses a different Chart Datum than MLLW called Columbia River Datum (CRD)
** This gap is presently being operationally filled with long-term Columbia River PORTS® partnership stations

Alaska

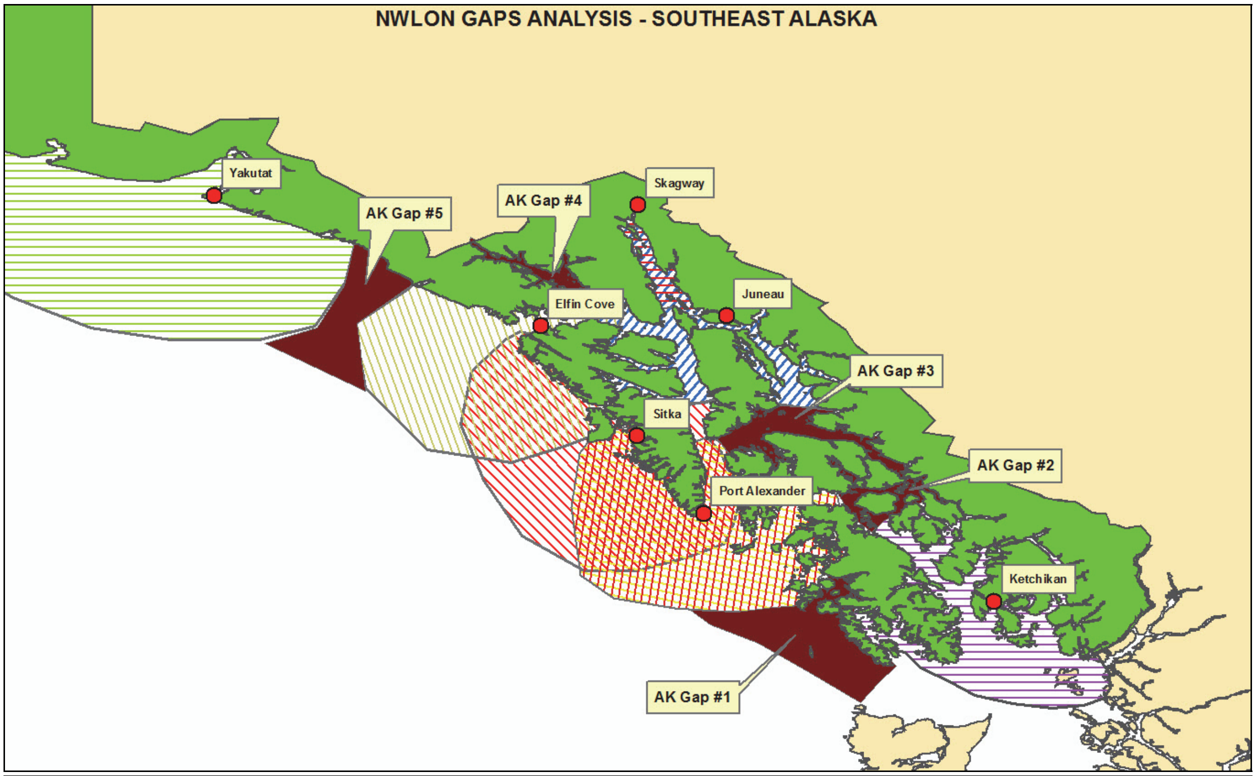

Figure 24. NWLON gaps analysis for southeast Alaska

1) Craig, Bucareli Bay, AK
2) Snow Passage, AK
3) Frederick Sound, AK
4) Glacier Bay, AK
5) Entrance to Dry Bay, AK

Note: AK gaps 2, 3, and 4 are in areas undergoing rapid uplift due to post-glacial rebound.

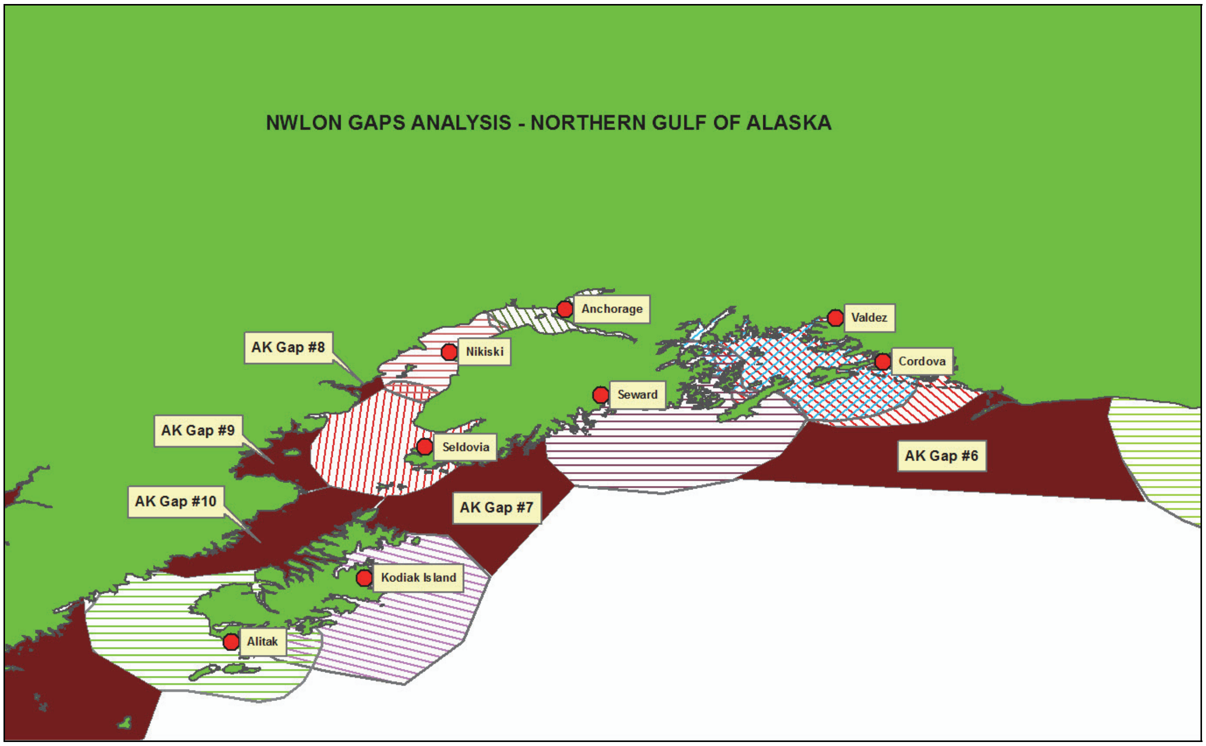

Figure 25. NWLON gaps analysis for the northern Gulf of Alaska

6) Cape St. Elias, Controller Bay, AK
7) Cook Inlet Entrance, AK
8) Tuxedni Bay, AK
9) Kamishak Bay, AK
10) Shelikof Straits, AK

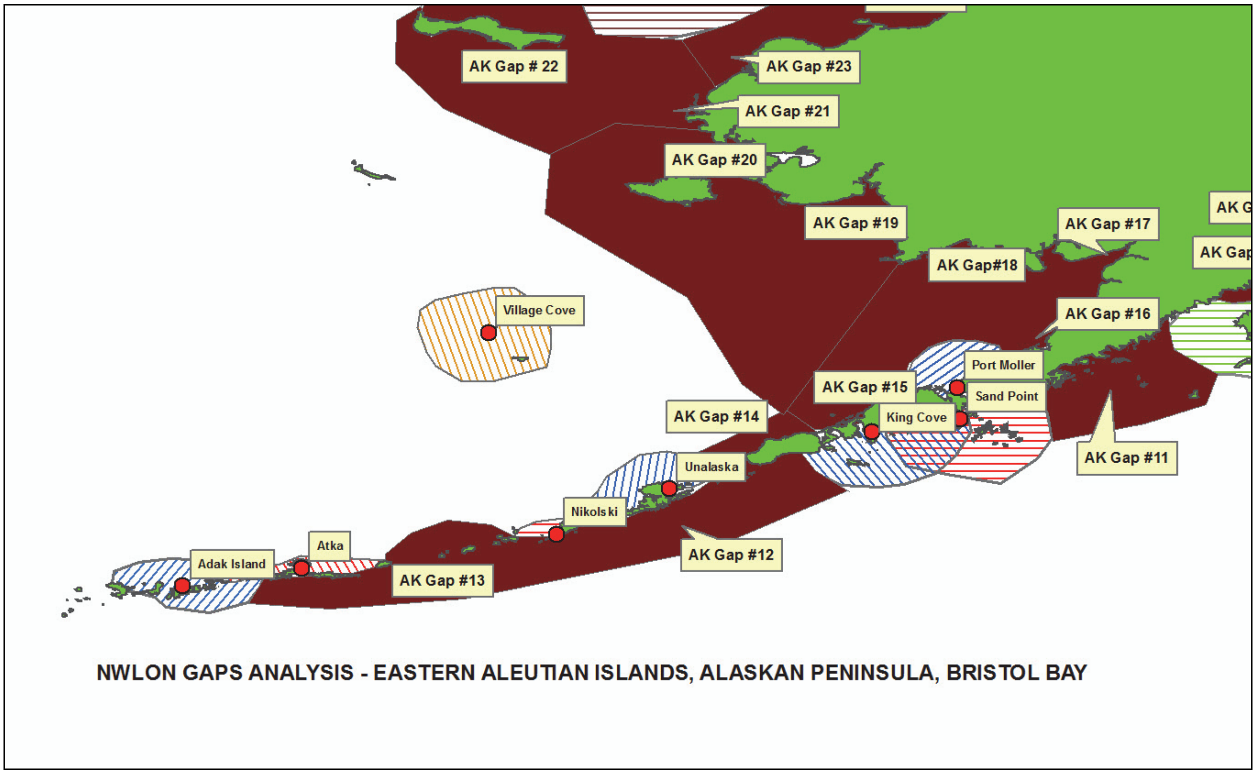

Figure 26. NWLON gaps analysis for western Alaska and the eastern Aleutian Islands

11) Port Wrangell to Chignik Bay, Alaska Peninsula
12) Aleutian Islands, South Side, Unimak Island to Unalaska Island
13) Aleutian Islands, South Side, Unalaska Island to Atka Island
14) North Side Unimak Island
15) North Side Aleutians East
16) Kvichak Bay Vicinity
17) Nushagak Bay
18) Hagemeister Island Vicinity
19) Kuskokwim Bay
20) Toksook Bay Vicinity, AK
21) Yukon River Delta

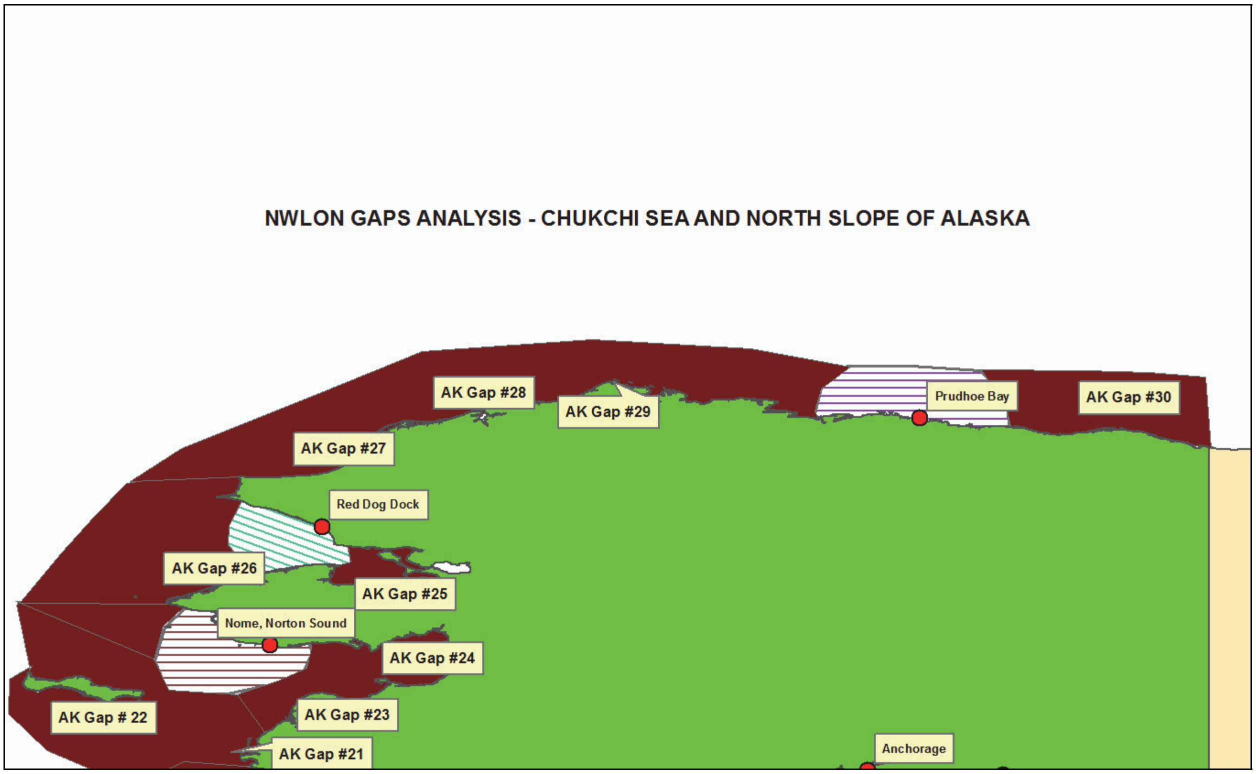

Figure 27. NWLON gaps analysis for Chukchi Sea and North Slope of Alaska

22) Eastern St. Lawrence Island
23) Stebbins, Southern Norton Sound
24) Eastern Norton Sound
25) Eastern Kotzebue Sound: This area transitions form tidal to non-tidal.
26) Bering Straits
27) Chukchi Sea, Cape Sabine Vicinity
28) Chukchi Sea, Icy Cape Vicinity
29) Pt. Barrow
30) Prudhoe Bay to Canadian Border

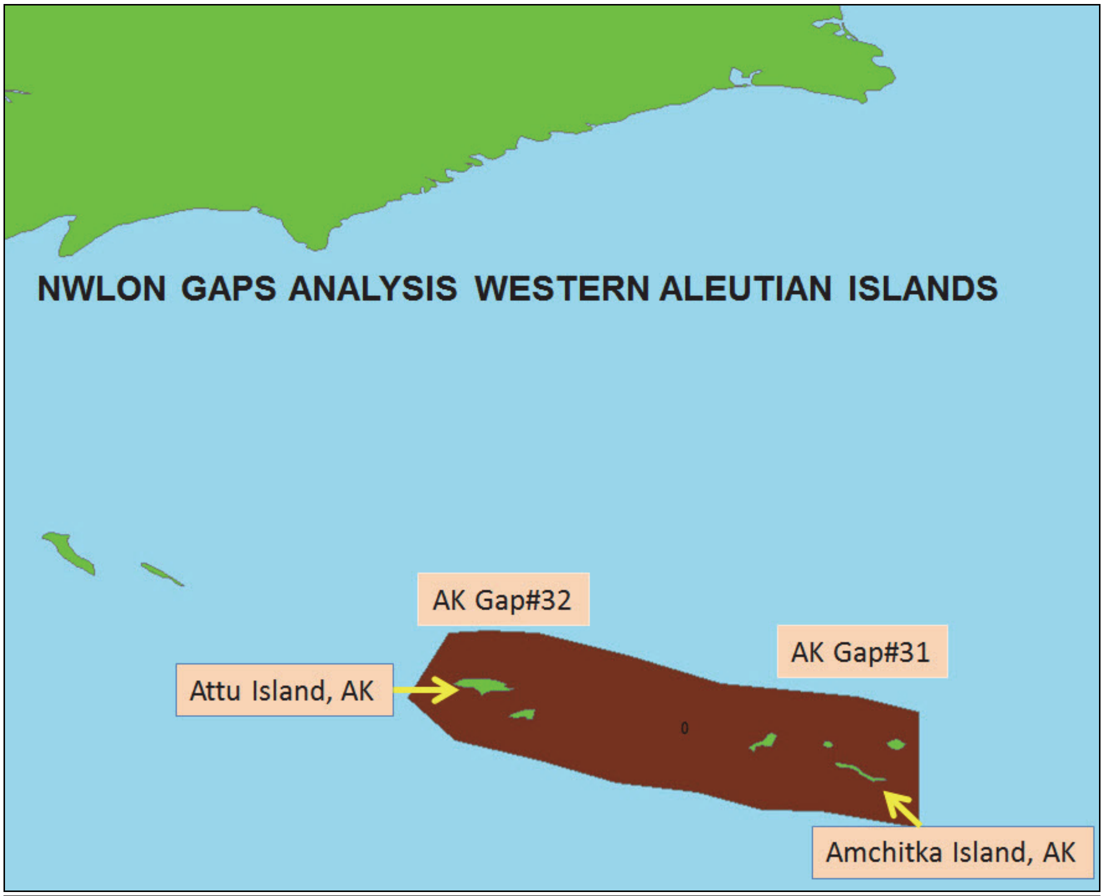

Figure 28. NWLON gaps analysis for the western Aleutian Islands

31) Amchitka Island
32) Attu Island

Hawaii

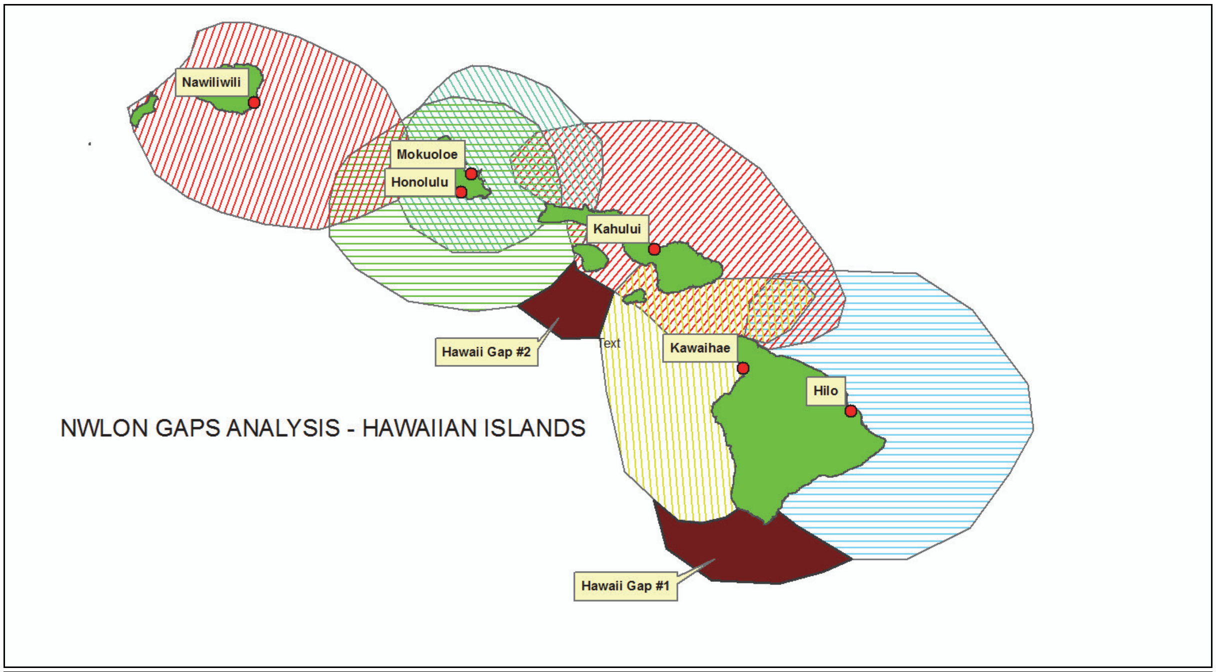

Figure 29. NWLON Gaps Analysis for Hawaii

1) Southeast Point of Hawaii Island, HA

2) South shore of Kaho O'Lowe Island, HA

ASSESSMENT OF GAPS AND SEA LEVEL TRENDS

Appendix 2 provides maps of the NWLON, NWLON gaps, and measured sea level trends at tide stations. Not all NWLON stations have long enough series lengths (30 years) to compute a reliable trend (Zervas 2009), however improved knowledge of gradients in sea level trends along the coast will be obtained in the future as the stations accrue more data. In general, the maps show fairly small changes in sea level trends along the coast such that that once gaps are filled, variations is sea level trends will be covered by the NWLON network (Figure 32). Figure33 illustrates the variability in sea level trends in three anomalous regions with large variations across the region.

One example of extreme geospatial variation sea level trends is in Louisiana (see Figure 33) where the diurnal tide dominates. Even though the tidal characteristics are similar, there is a strong gradient in relative mean sea level trends due to local and regional subsidence. Because of the disparity in relative mean sea level trends (Zervas, 2001) the NWLON station at Grand Isle, LA (+9.85mm/yr.) and Dauphin Island, AL (2.93mm/yr.) for instance, cannot be used to provide datum control in Lake Pontchartrain (~ 7.0mm/yr. (USACE, 2006)). Another example is in Southeast Alaska. Both Juneau (inside) and Sitka (outside) have similar tidal characteristics. However, Juneau (-12.69 mm/yr.) has a much higher rate of relative sea level fall than Sitka (-2.17 mm/yr.). Both have very similar ranges and times of tide; however neither tide station should be used to provide datum control for subordinate stations that would be established near the other station due to the bias introduced by such a large difference in relative sea level trend. In the Pacific Northwest coast, coastal stations have very similar tidal characteristics, however sea level trends vary from positive to negative due to the varying rates of tectonic movement in the region. Filling of NWLON gaps with long-term stations will eventually assist in filling in information on spatial variability of relative sea level trends. Analysis of long relative sea level trends from tide stations has been found to be useful in estimating local rates of vertical land movement (Zervas et al, 2013).

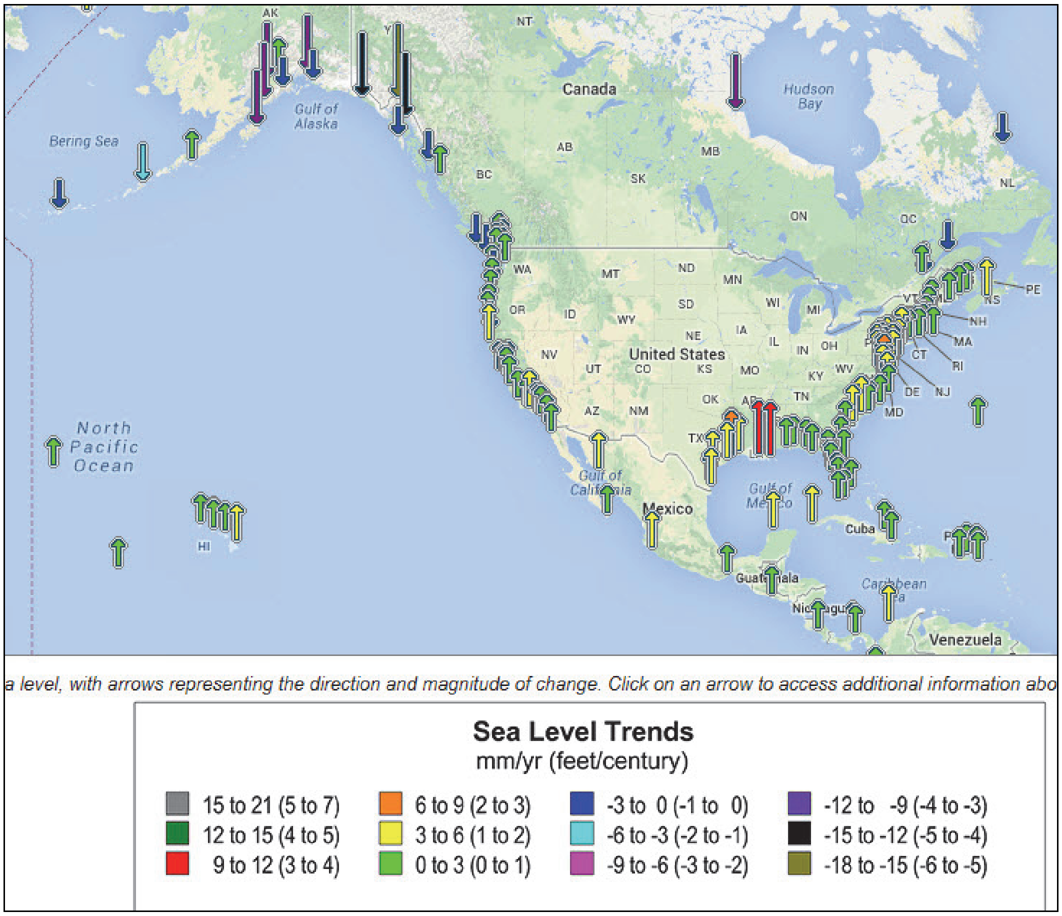

Figure 30. Relative sea level trends for coastal US

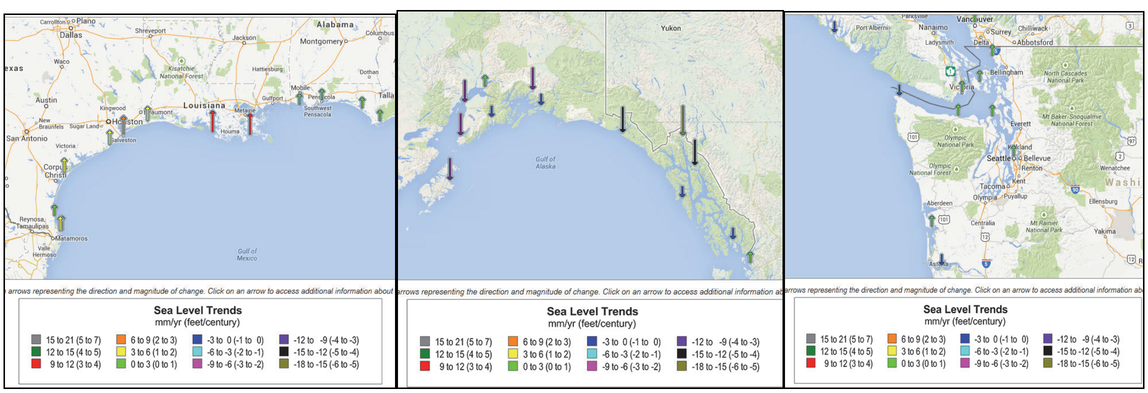

Figure 31. Relative sea level trends at NWLON stations in the Gulf of Mexico, southeast Alaska, and the Pacific Northwest

The interplay of the polygons of coverage, the gaps in coverage and sea level trends must be kept in mind in project planning and new datum calculation. Filling of the NWLON gaps in Southeast Alaska (figure 32) and accruing long-term data sets from the new NWLON stations will also help fill-in gaps in understanding the spatial variability of the regional sea level trends. It is not yet clear, for instance which control station should be used to determine datums at Elfin

Cove, AK and Port Alexander while waiting to accrue 19-years of data for a first-reduction computation. Even though close in tidal characteristics to nearby NWLON stations, as suggested by the coverage polygons, their sea level trends could be quite different.

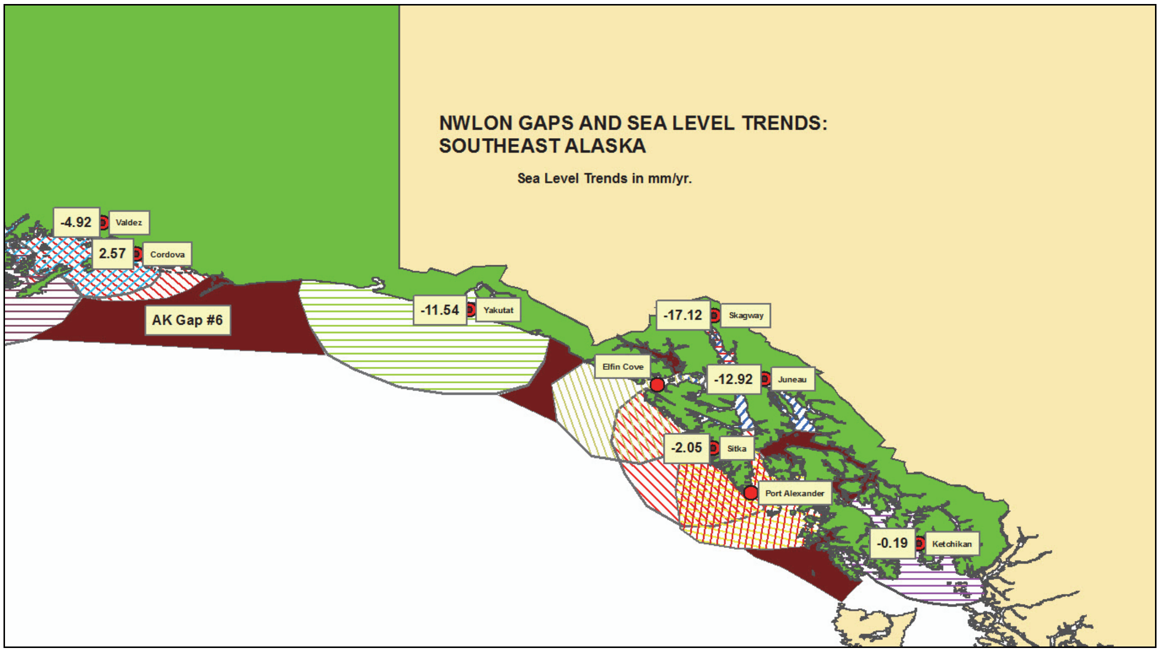

Figure 32. NWLON gaps and sea level trends for southeast Alaska

The importance needing to know geospatial variability of sea level trends for a particular gap can be illustrated by looking at tidal datum computation results for a typical subordinate station using various nearby existing NWLON stations. Table 4 shows equivalent 19-year tidal datums elevations based on a one-month simultaneous comparison for tertiary tide station at Wrangell, AK. The differences datum elevations using different control stations for the same observations are several centimeters, mainly due to different sea level trends at each control station. The difference in range of tide (expressed as a range ratio) is larger relative to Sitka than at the other two control stations, however the sea level trend at Sitka could be more applicable at Wrangell. It is unknown without additional information. A new NWLON installed in this gap would eventually mitigate the datum uncertainties in the region after accruing a long enough time series for estimating a local sea level trend.

Table 4. Comparison of tidal datum elevations for a one-month tertiary station in southeast Alaska

Wrangell Point, AK	Control Station Used		
Datum Elevation (m) Relative to Station Datum	Juneau	Sitka	Ketchikan
Sea Level Trend (mm/yr.)	-17.12	-2.05	-0.19
MSL (one month)	-0.223	-0.114	-0.073
MLLW (one month)	-2.726	-2.628	-2.596
Range Ratio	x0.976	x1.620	x1.035

LIMITATIONS

There are limitations to the broad assumptions of the methodology used in this study. While this study assumes that the error will be mainly driven by the factored geographic distance, range ratio, and time difference determined by the Bodnar analysis and by differences in sea level trends, those assumptions are an over simplification in areas with extremely fast changing tidal characteristics and where differences in vertical land movement become extremely complicated within small distances. Examples for tidal variations would be in a closely knit amphidromic point in which co-tidal lines and the interplay of semidiurnal and diurnal tidal constituents and changes in tide types are not smoothly varying; in areas of tidal rivers were the effects of river flow need to be factored into error budget considerations; and in areas where the effects of meteorological forcing dominate the tidal signal (Parker, 2007). The actual planning of survey or project control requires a more detailed analysis for each project area than the broader analysis used for this gaps identification.

The polygons describing the gaps were based on the error budget and equation for a typical 3-month tertiary tide station installation. Polygons of coverage could be extended and have more overlap if one-year secondary stations were established and the Bodnar equations for one-year series length were used to meet the same 0.12ft. target datum error.

ROLE OF PARTNERSHIPS

Partnerships with external organizations continue to be leveraged to help meet NWLON mission requirements. Many of the gaps reported here are being operationally/temporarily filled with long-term partnership stations that are established to meet local requirements and are operated to NOAA NWLON standards to provide timely, accurate and reliable data.

For instance, nine (9) of the gaps reported here have long-term PORTS® water level stations in operation. A few have been in operation nearly 19-years. Although not yet in for 19-years, the rest of them can effectively be used as control stations for shorter-term subordinate stations installed for various NOS hydrographic, shoreline, and VDatum projects. There are eleven (11) NWLON gaps in Texas. Three (3) of the gaps have existing long-term PORTS® stations installed. The other 8 gaps have operational stations maintained by Conrad Blucher Institute (CBI, 2014) as part of the Texas Coastal Ocean Observation Network (TCOON). CO-OPS has an agreement with TCOON for open exchange of data and data products such that NOAA uses TCOON data for operational purposes and these long-term stations can be used to meet NOAA datum control requirements.

There are various other partnerships throughout the network that are being similarly leveraged (as identified in the above listings). For all of these partnerships, NOAA relies upon partnership funding to keep the stations in over the long-term. The partnership stations would not officially fill an NWLON gap until they could be incorporated into the process with long-term federal funding .

SUMMARY

The analysis results here have identified approximately 111 gaps in NWLON coverage beyond the 210 NWLON stations deployed as of FY2014. Forty-three (43) gaps are located along the east coast, 28 in the gulf coast, 6 gaps on the west coast, 32 gaps in Alaska, and 2 in Hawaii. The 111 NWLON gaps identified in this report plus the three (3) NWLON gaps identified in the Great Lakes NWLON (Gill, 2014) results in a total of 114 NWLON gaps. Added to the existing 210 NWLON stations, the approximate target NWLON size would be 324 stations.

A deterministic approach to estimating the areas of NWLON coverage for datum determination at nearby subordinate tide stations has been developed. The approach uses the basic error analyses of Swanson (1974) and the regression error analyses of Bodnar (1981) to estimate regions of coverage for each individual NWLON station. Using GIS tools, the information is displayed on maps of coverage polygons. The GIS output is then used to identify geographic areas that represent gaps in the NWLON. The datum error polygons can be used for multiple purposes for short-term and long-term management of the NWLON. The assessment of the gaps with the information on regional variations in relative sea level trends also show that filling the gaps will assist in providing even better coverage, especially in areas such as most of the coasts of Alaska and Louisiana. However, no gaps were identified solely for requiring new information on sea level trends.

This analysis is being used for strategic planning and prioritization of locations to establish new NWLON stations as the network grows towards the optimum number of stations. It is being used to make decisions regarding utilization of resources for the importance of bringing an NWLON station back on line immediately or if a nearby station can be used effectively as a back-up until reconstruction or repair can take place. A good example of the utility of the analysis is for Ocean Springs, Mississippi. The Ocean Springs station, which is on the current list of 210 NWLON stations, was destroyed during Hurricane Katrina but has not been re-established. Since that time, a new NWLON has been established nearby at Pascagoula. This updated analysis shows that because of the original gap is now filled by Pascagoula, a new NWLON is no longer required at Ocean Springs and resources can be allocated to another location.

The technical approach is also being used to make operational decisions for optimal locations to establish stations for hydrographic and shoreline survey support. A significant advancement is that this approach is being used as a replacement for the broad regional generalized accuracies of Swanson with location specific estimates of errors for datum determination at subordinate stations. This effort has allowed for more precise error estimates to be input to the total error budgets for all applications.

As a next step towards adding additional stations to the NWLON, the GIS layers created by this effort have been used to evaluate the locations of other Federal, state, and regional water level observation networks for possible leveraging and partnership opportunities (i.e. National Park Service and NERRS). NOAA has some key State and federal partners who are or have worked with CO-OPS to establish and operate their own local networks that closely match NOS operating standards. Examples are the Florida Department of Environmental Protection (FLDEP) and the Texas Coastal Ocean Observing Network (TCOON). In some instances, stations independently operated by these partners are located within NWLON. Other potential partners include the US Army Corps of Engineers (USACE) and the U.S. Geological Survey (USGS). CO-OPS has recently reached out to our stakeholder community asking for input as to prioritization for filling specific NWLON gaps.

ACKNOWLEDGMENTS

The author appreciates all of the dedication and hard work of CO-OPS and predecessor organization employees that has resulted in a National Water Level Observation Network that continues to serve the nation every day. The co-author on the original report, Kathleen Fisher, no longer works for NOAA, however her contribution is recognized. Brenda Via is acknowledged for her expertise in preparation for publication.

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APPENDIX

APPENDIX 1. National Water Level Observation Network (NWLON) Tide Station List as of August 2014

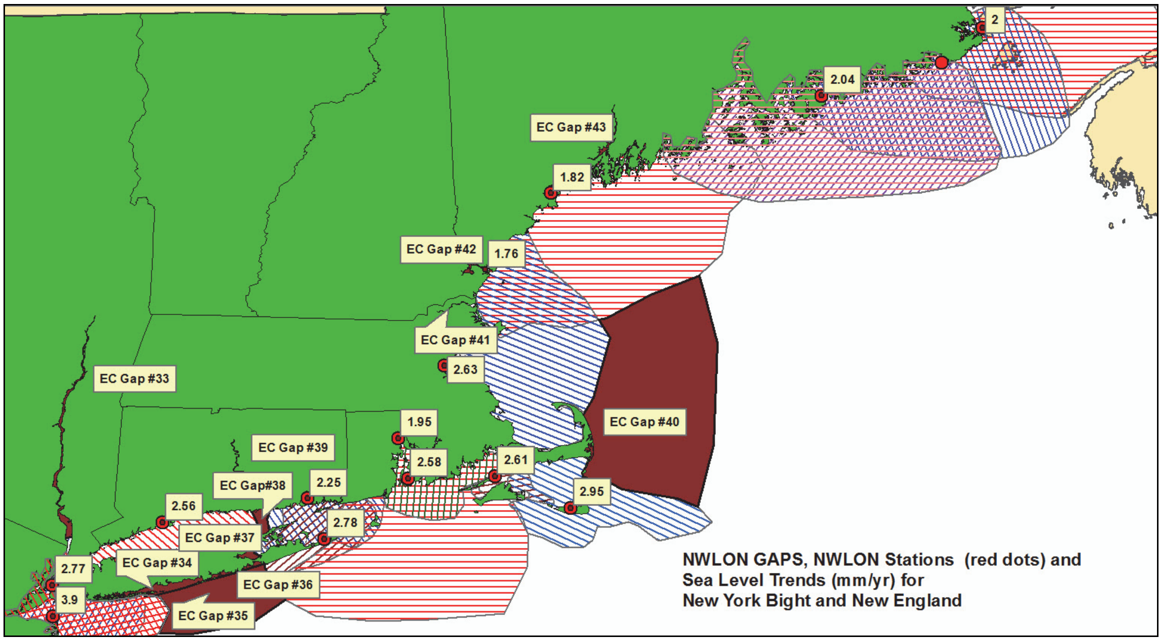
Station ID	Tide Station Name	LAT	LONG	Date Established	Length of Series (years)
1611400	Nawiliwili, HI	21.955	-159.357	1955	59
1612340	Honolulu, HI	21.307	-157.867	1905	109
1612480	Mokuoloe, HI	21.437	-157.793	1957	57
1615680	Kahului, HI	20.898	-156.472	1947	67
1617433	Kawaihae, HI	20.040	-155.832	1990	24
1617760	Hilo, HI	19.730	-155.057	1927	87
1619910	Sand Island, Midway	28.212	-177.360	1947	67
1630000	Guam	13.442	144.653	1993	21
1770000	Pago Pago	-14.280	-170.690	1948	66
1820000	Kwajalein, Marshall Islands	8.737	167.738	1946	68
1890000	Wake Island	19.290	166.618	1950	64
8410140	Eastport, ME	44.903	-66.985	1929	85
8411060	Cutler Farris Wharf, ME	44.642	-67.297	2010	4
8413320	Bar Harbor, ME	44.392	-68.205	1947	67
8418150	Portland, ME	43.657	-70.247	1912	102
8443970	Boston, MA	42.355	-71.052	1921	93
8447930	Woods Hole, MA	41.523	-70.672	1932	82
8449130	Nantucket Island, MA	41.285	-70.097	1965	49
8452660	Newport, RI	41.505	-71.327	1930	84
8454000	Providence, RI	41.807	-71.402	1938	76
8461490	New London, CT	41.355	-72.087	1938	76
8467150	Bridgeport, CT	41.173	-73.182	1964	50
8510560	Montauk, NY	41.048	-71.960	1947	67
8516945	Kings Point, NY	40.810	-73.765	1931	83
8518750	The Battery, NY	40.700	-74.015	1856	158
8531680	Sandy Hook, NJ	40.467	-74.010	1932	82
8534720	Atlantic City, NJ	39.355	-74.418	1911	103
8536110	Cape May, NJ	38.968	-74.960	1961	53
8545240	Philadelphia, PA	39.933	-75.142	1900	114
8551910	Reedy Point, DE	39.558	-75.573	1956	58
8557380	Lewes, DE	38.782	-75.120	1919	95
8570283	Ocean City Inlet, MD	38.328	-75.092	1998	16
8571421	Bishops Head, MD	38.220	-76.038	2005	9
8571892	Cambridge, MD	38.573	-76.068	1943	71
8574680	Baltimore, MD	39.267	-76.578	1902	112
8575512	Annapolis, MD	38.983	-76.480	1928	86

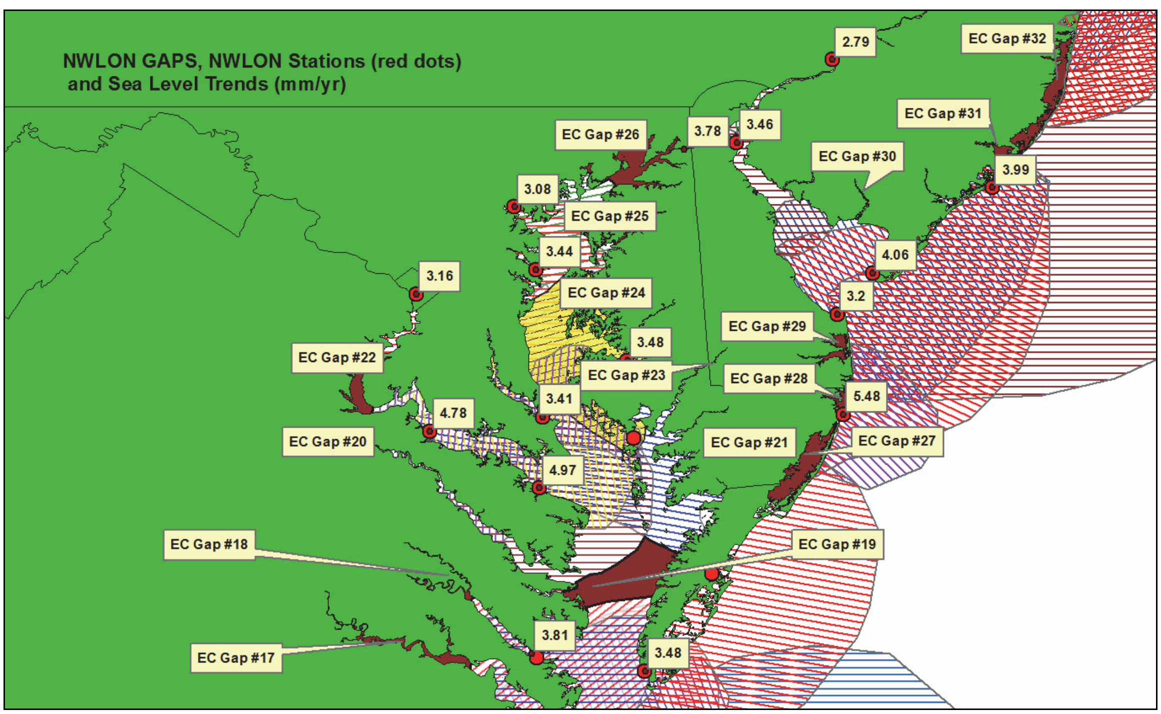
8577330	Solomons Island, MD	38.317	-76.452	1937	77
8594900	Washington, DC	38.873	-77.022	1924	90
8631044	Wachapreague, VA	37.607	-75.687	1996	18
8632200	Kiptopeke, VA	37.167	-75.988	1951	63
8635150	Colonial Beach, VA (relocate to Dahlgren)	38.252	-76.960	1972	42
8635750	Lewisetta, VA	37.995	-76.465	1974	40
8637689	Yorktown USCG Training Ctr, VA	37.227	-76.478	2004	10
8638610	Sewells Point, VA	36.947	-76.330	1927	87
8638863	Chesapeake Bay Br.Tunnel, VA	36.967	-76.113	1975	39
8651370	Duck, NC	36.183	-75.747	1978	36
8652587	Oregon Inlet, NC	35.795	-75.548	1977	37
8654467	USCG Station Hatteras, NC	35.208	-75.703	2010	4
8656483	Beaufort (Duke Marine Lab), NC	34.720	-76.670	1953	61
8658120	Wilmington, NC	34.227	-77.953	1935	79
8658163	Wrightsville Beach, NC	34.210	-77.795	2004	10
8661070	Springmaid Pier, SC	33.655	-78.918	1957	57
8665530	Charleston, SC	32.782	-79.925	1921	93
8670870	Fort Pulaski, GA	32.033	-80.902	1935	79
8720030	Fernandina Beach, FL	30.672	-81.465	1897	117
8720218	Mayport, FL	30.397	-81.430	1928	86
8721604	Trident Pier, FL	28.415	-80.593	1994	20
8722670	Lake Worth Pier, FL	26.612	-80.033	2010	4
8723214	Virginia Key, FL	25.732	-80.162	1996	18
8723970	Vaca Key, FL	24.718	-81.017	1971	43
8724580	Key West, FL	24.712	-81.105	1913	101
8725110	Naples, FL	24.553	-81.808	1965	49
8725520	Fort Myers, FL	26.130	-81.807	1965	49
8726520	St. Petersburg, FL	26.647	-81.872	1947	67
8726724	Clearwater Beach, FL	27.760	-82.627	1973	41
8727520	Cedar Key, FL	27.978	-82.832	1914	100
8728690	Apalachicola, FL	29.135	-83.032	1967	47
8729108	Panama City, FL	29.727	-84.982	1973	41
8729210	Panama City Beach, FL	30.152	-85.667	1993	21
8729840	Pensacola, FL	30.213	-85.878	1923	91
8735180	Dauphin Island, AL	30.403	-87.212	1966	48
8737048	Mobile, AL	30.250	-88.075	2002	12
8741533	Pascagoula, MS	30.708	-88.043	2005	9
8743281	Ocean Springs, MS	30.368	-88.563	not re-established	0
8747437	Bay Waveland YC, MS	30.325	-89.325	1997	17
8760922	Pilots Station, SW Pass, LA	28.932	-89.407	1996	18
8761305	Shell Beach, Lake Borgne, LA	29.868	-89.673	2008	6
8761724	Grand Isle, LA	29.263	-89.957	1947	67
8761927	USCG New Canal Station, LA	30.027	-90.113	2005	9
8762372	East Bank 1, Bayou LaBranche	30.050	-90.368	2003	11
8764044	Berwick, LA	29.448	-91.338	2003	11
8764227	LAWMA, Amerada Pass, LA	29.668	-91.238	2006	8

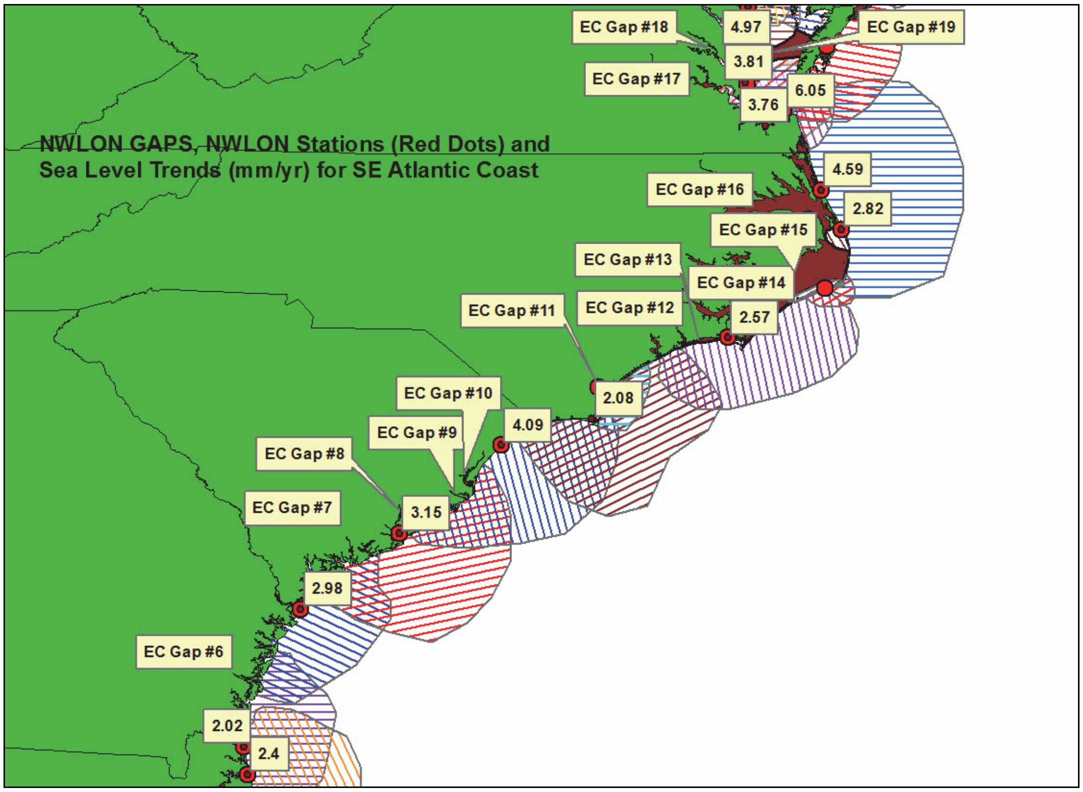
8766072	Freshwater Canal Locks, LA	29.555	-92.305	2005	9
8767816	Lake Charles, LA	30.223	-93.221	2002	12
8768094	Calcasieu Pass, LA	29.765	-93.343	2002	12
8770570	Sabine Pass, TX	29.730	-93.870	1958	56
8771341	Galveston Bay Entrance, N Jetty, TX	29.310	-94.793	2001	13
8771450	Galveston Pier 21, TX	29.357	-94.725	1908	106
8772447	USCG Freeport, TX	28.948	-95.308	2006	8
8774770	Rockport, TX	28.022	-97.047	1948	66
8775870	Corpus Christi, TX	27.580	-97.217	1983	31
8779770	Port Isabel, TX	26.060	-97.215	1944	70
9410170	San Diego, CA	32.713	-117.173	1906	108
9410230	La Jolla, CA	32.867	-117.258	1924	90
9410660	Los Angeles, CA	33.720	-118.272	1923	91
9410840	Santa Monica, CA	34.008	-118.500	1933	81
9411340	Santa Barbara, CA	34.408	-119.685	1973	41
9412110	Port San Luis, CA	35.177	-120.760	1945	69
9413450	Monterey, CA	36.605	-121.888	1973	41
9414290	San Francisco, CA	37.807	-122.465	1854	160
9414750	Alameda, CA	37.772	-122.298	1939	75
9415020	Point Reyes, CA	37.997	-122.975	1975	39
9415144	Port Chicago, CA	38.057	-122.038	1976	38
9416841	Arena Cove, CA	38.913	-123.708	1996	18
9418767	North Spit, CA	40.767	-124.217	1977	37
9419750	Crescent City, CA	41.745	-124.183	1933	81
9431647	Port Orford, OR	42.740	-124.497	1977	37
9432780	Charleston, OR	43.345	-124.322	1970	44
9435380	South Beach, OR	44.625	-124.043	1967	47
9437540	Garibaldi, OR	45.555	-123.912	1970	44
9439040	Astoria, OR	46.208	-123.767	1925	89
9440422	Longview, WA	46.107	-122.955	2002	12
9440910	Toke Point, WA	46.708	-123.965	1973	41
9441102	Westport, WA	46.908	-124.110	2006	8
9442396	La Push, WA	47.913	-124.637	2002	12
9443090	Neah Bay, WA	48.368	-124.617	1934	80
9444090	Port Angeles, WA	48.125	-123.440	1975	39
9444900	Port Townsend, WA	48.112	-122.758	1972	42
9447130	Seattle, WA	47.605	-122.338	1898	116
9449424	Cherry Point, WA	48.863	-122.758	1973	41
9449880	Friday Harbor, WA	48.547	-123.010	1934	80
9450460	Ketchikan, AK	55.333	-131.625	1919	95
9451054	Port Alexander, AK	56.246	-134.647	2007	7
9451600	Sitka, AK	57.052	-135.342	1924	90
9452210	Juneau, AK	58.298	-134.412	1936	78
9452400	Skagway, AK	59.450	-135.327	1944	70
9452634	Elfin Cove, AK	58.193	-136.343	2005	9
9453220	Yakutat, AK	59.548	-139.735	1979	35

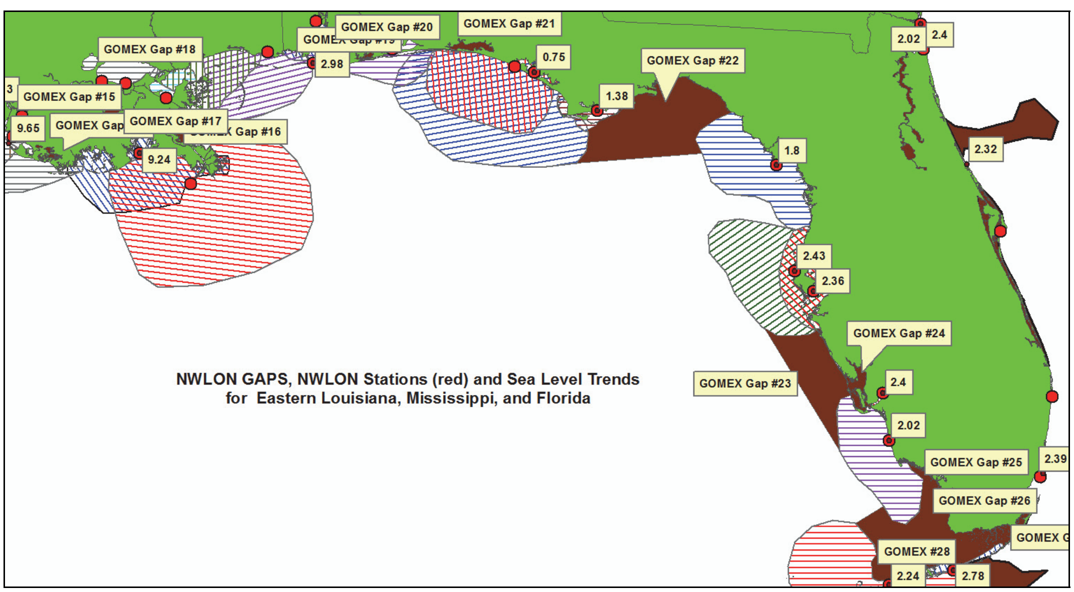
9454050	**Cordova, AK**	**60.558**	**-145.753**	**1979**	**35**
9454240	**Valdez, AK**	**61.125**	**-146.362**	**1979**	**35**
9455090	**Seward, AK**	**60.120**	**-149.427**	**1964**	**50**
9455500	**Seldovia, AK**	**59.440**	**-151.720**	**1964**	**50**
9455760	**Nikiski, AK**	**60.683**	**-151.398**	**1973**	**41**
9455920	**Anchorage, AK**	**61.238**	**-149.890**	**1972**	**42**
9457292	**Kodiak Island, AK**	**57.732**	**-152.512**	**1975**	**39**
9457804	**Alitak, AK**	**56.898**	**-154.247**	**2006**	**8**
9459450	**Sand Point, AK**	**55.337**	**-160.502**	**1972**	**42**
9459881	**King Cove, AK**	**55.062**	**-162.327**	**2005**	**9**
9461380	**Adak Island, AK**	**51.863**	**-176.632**	**1957**	**57**
9461710	**Atka, AK**	**52.232**	**-174.173**	**2006**	**8**
9462450	**Nikolski, AK**	**52.942**	**-168.872**	**2006**	**8**
9462620	**Unalaska, AK**	**53.880**	**-166.537**	**1957**	**57**
9463502	**Port Moller, AK**	**55.990**	**-160.562**	**2006**	**8**
9464212	**Village Cove, Pribilof Is, AK**	**57.125**	**-170.285**	**2002**	**12**
9468756	**Nome, AK**	**64.500**	**-165.430**	**1992**	**22**
9491094	**Red Dog Dock, AK**	**67.577**	**-164.065**	**2003**	**11**
9497645	**Prudhoe Bay, AK**	**70.400**	**-148.527**	**1993**	**21**
9751364	**Christiansted, St Croix, VI**	**17.750**	**-64.705**	**2006**	**8**
9751381	**Lameshur Bay, St Johns, VI**	**18.320**	**-64.725**	**2006**	**8**
9751401	**Lime Tree Bay, VI**	**17.697**	**-64.753**	**1977**	**37**
9751639	**Charlotte Amalie, VI**	**18.335**	**-64.920**	**1975**	**39**
9752235	**Culebra, PR**	**18.302**	**-65.303**	**2005**	**9**
9752695	**Vieques Island, PR**	**18.093**	**-65.472**	**2005**	**9**
9755371	**San Juan, PR**	**18.458**	**-66.117**	**1962**	**52**
9759110	**Magueyes Island, PR**	**17.972**	**-67.047**	**1955**	**59**
9759412	**Aguadilla Pier, PR**	**18.458**	**-67.168**	**2006**	**8**
9759938	**Mona Island, PR**	**18.090**	**-67.938**	**2006**	**8**

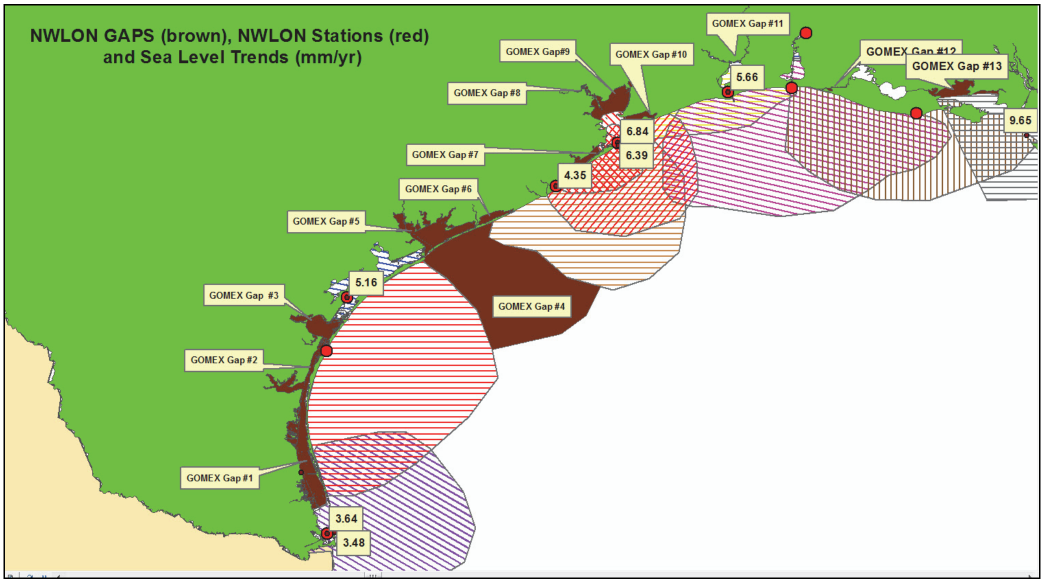
APPENDIX 2. NWLON Gaps, NWLON Stations and Sea Level Trends

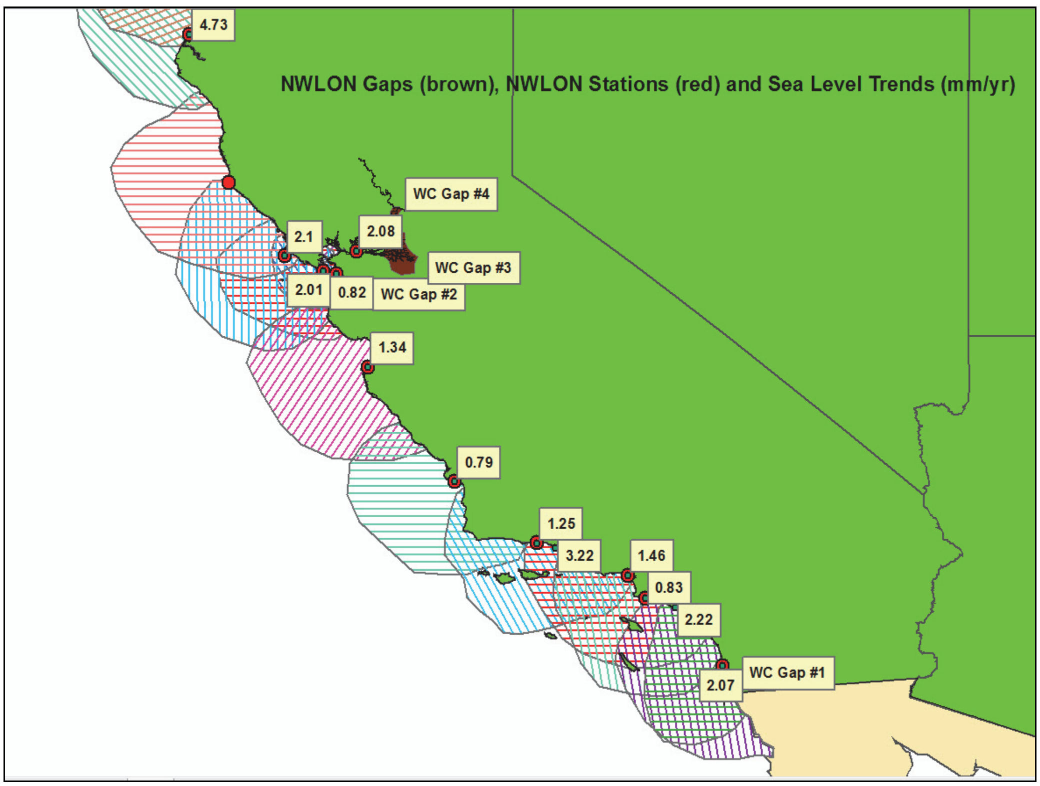


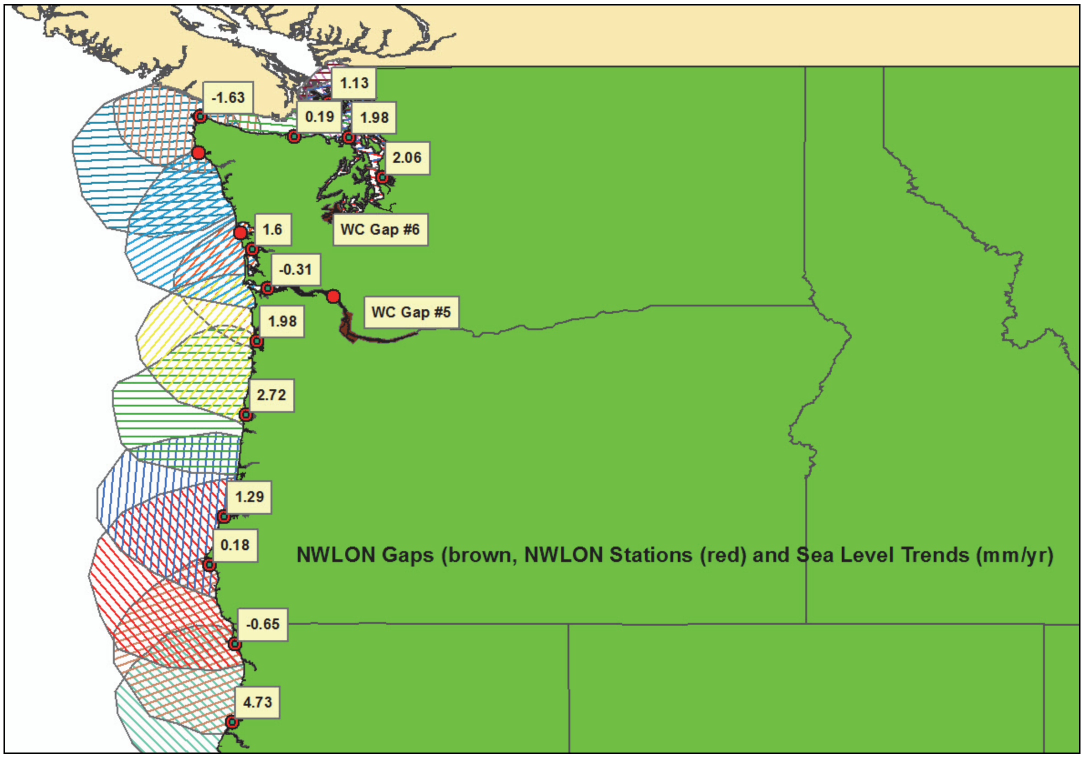


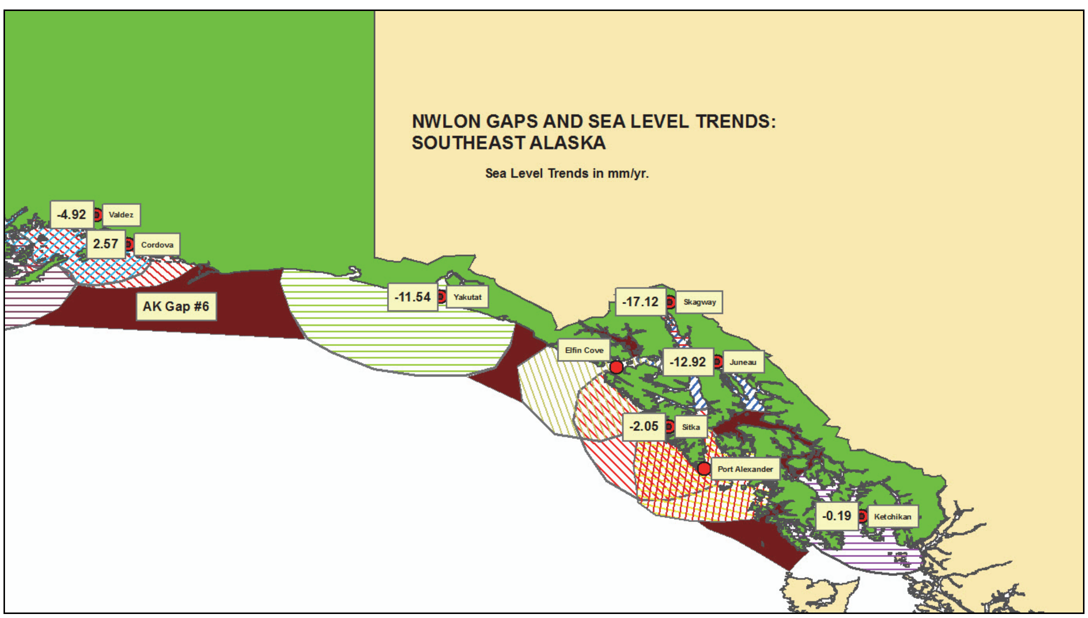

NWLON GAPS, NWLON Stations (Red Dots) and
Sea Level Trends (mm/yr) for SE Atlantic Coast
EC Gap #18
4.97
EC Gap #19
3.81
EC Gap #17
6.05
3.76
4.59
EC Gap #16
2.82
EC Gap #15
EC Gap #13
EC Gap #14
EC Gap #11
EC Gap #12
2.57
2.08
EC Gap #10
4.09
EC Gap #9
EC Gap #8
EC Gap #7
3.15
2.98
EC Gap #6
2.02
2.4

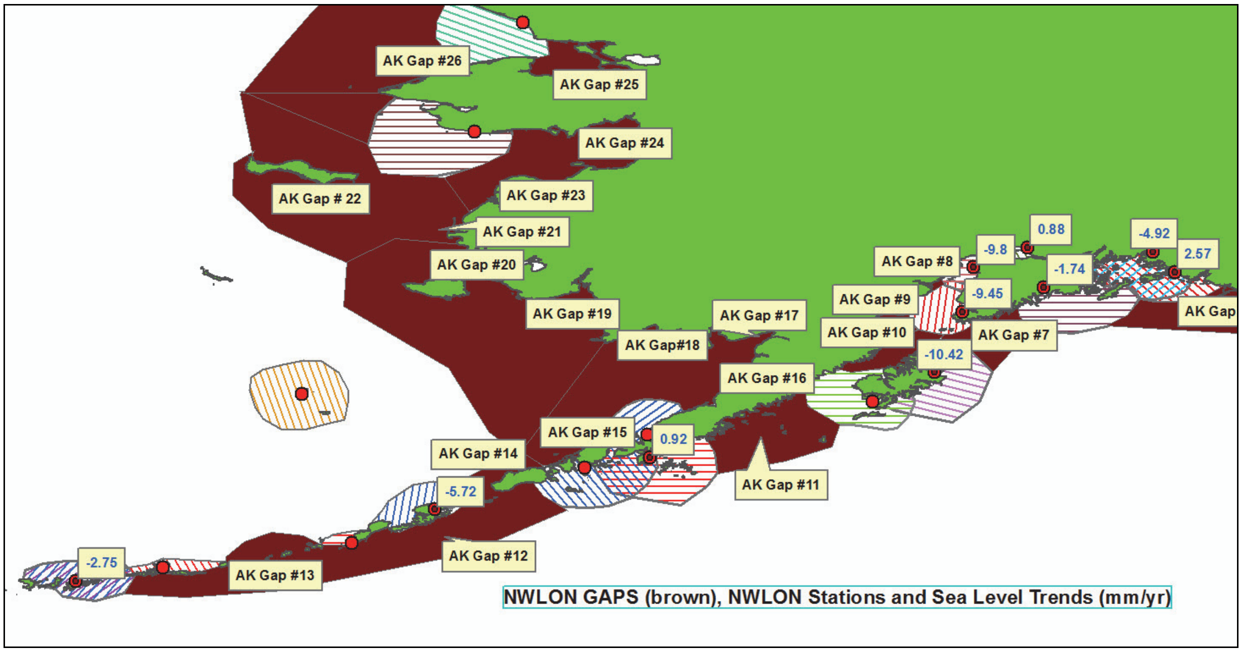

GOMEX Gap #20
GOMEX Gap #21
GOMEX Gap #18
2.98
0.75
GOMEX Gap #22
2.02
2.4
GOMEX Gap #15
1.38
9.65
GOMEX Gap #17
9.24
2.32
1.8
2.43
2.36
GOMEX Gap #24
NWLON GAPS, NWLON Stations (red) and Sea Level Trends
for Eastern Louisiana, Mississippi, and Florida
GOMEX Gap #23
2.4
2.02
GOMEX Gap #25
2.39
GOMEX Gap #26
GOMEX #28
2.24
2.78


NWLON GAPS (brown), NWLON Stations (red)
and Sea Level Trends (mm/yr)
GOMEX Gap #11
GOMEX Gap#9
GOMEX Gap #10
GOMEX Gap #13
5.66
GOMEX Gap #8
9.65
6.84
GOMEX Gap #7
6.39
4.35
GOMEX Gap #6
GOMEX Gap #5
5.16
GOMEX Gap #3
GOMEX Gap #4
GOMEX Gap #2
GOMEX Gap #1
3.64
3.48


4.73
NWLON Gaps (brown), NWLON Stations (red) and Sea Level Trends (mm/yr)
WC Gap #4
2.1
2.08
WC Gap #3
2.01
0.82
WC Gap #2
1.34
0.79
1.25
3.22
1.46
0.83
2.22
WC Gap #1
2.07


NWLON Gaps (brown, NWLON Stations (red) and Sea Level Trends (mm/yr)
1.13
-1.63
0.19
1.98
2.06
1.6
WC Gap #6
-0.31
WC Gap #5
1.98
2.72
1.29
0.18
-0.65
4.73


NWLON GAPS AND SEA LEVEL TRENDS:
SOUTHEAST ALASKA
Sea Level Trends in mm/yr.
-4.92
Valdez
2.57
Cordova
AK Gap #6
-11.54
Yakutat
-17.12
Skagway
Elfin Cove
-12.92
Juneau
-2.05
Sitka
Port Alexander
-0.19
Ketchikan


AK Gap #26
AK Gap #25
AK Gap #24
AK Gap # 22
AK Gap #23
AK Gap #21
AK Gap #20
AK Gap #19
AK Gap #17
AK Gap#18
AK Gap #16
AK Gap #15
AK Gap #14
0.92
-5.72
AK Gap #11
AK Gap #12
-2.75
AK Gap #13
AK Gap #8
-9.8
0.88
-4.92
2.57
-1.74
AK Gap #9
-9.45
AK Gap #10
AK Gap #7
-10.42
AK Gap
NWLON GAPS (brown), NWLON Stations and Sea Level Trends (mm/yr)

APPENDIX 3. National Water Level Observation Network (NWLON) Station Configuration

All NWLON stations maintain a high degree of accuracy and reliability, and are considered "multipurpose", providing both high rate, real-time data, and long-term sea level trends. NWLON station design and construction is quite robust, and great care is taken in obtaining long-term continuous and valid water level data. Redundancy is built in at all design levels (sensor, power, communications, and data logger) to ensure continuous data and minimize expensive emergency repair trips. Many stations have now been operating continuously for over 100 years. The tide station at San Francisco has been continuously operating for over 150 years. Environmental enclosures are designed to last several years and underwater components are designed to withstand harsh coastal wave and current environments. Tide station platforms may be elevated to withstand storm surge. In colder regions, station configurations are designed to withstand ice conditions. All stations have an associated network of bench marks that are surveyed annually to ensure vertical stability of the gauge, and preserve a consistent data record in case of slow or sudden vertical movement due to pier deterioration, earthquakes, glacial rebound, ship/dock collisions, or station destruction by coastal storms. If destroyed, a new station can be established relative to the same vertical reference datum using the established bench mark elevations. Differential leveling is done on a yearly basis between the water level sensor and the bench marks to ensure vertical stability of the sensor relative to the land and to ensure the bench marks are vertically stable among themselves. Efforts are also underway to systematically connect all long-term tide stations to the National Spatial Reference System (maintained by NOAA's National Geodetic Survey) where relationships do not currently exist between local tidal datums and geodetic vertical datums, such as the North American Vertical Datum of 1988 (NAVD88). This is now performed using repeat static GPS observations at each station and in some cases by colocation with an NGS Continuously Operating Reference Station (CORS). Annual routine Operations and Maintenance (O&M) is also performed at each NWLON station to make any minor necessary repairs, upgrades, and/or to recalibrate the sensors as necessary. Figure A3-1 illustrates a common NWLON station configuration that features both acoustic primary and pressure backup sensors, which is found in many locations, particularly along the East and Gulf coasts, and in the Caribbean. Many Alaska NWLON primary gauge configurations feature a dual orifice pressure sensor configuration because the severe effects of the ice can destroy the acoustic sensors' protective wells and also to account for the fact that downward looking acoustic sensors cannot measure the correct water levels when the water is frozen or ice accumulates in the sounding tube. At each station one data collection platform (DCP) is designated as a primary, and the other as a backup. At some very remote locations a fully redundant set of DCPs and sensors are installed to reduce data loss and avoid very expensive emergency trips. Lower precision strain-gauge pressure sensors are typically used for the backup system. This two-DCP configuration has several applications. Not only do the redundant observations limit the potential for data gaps associated with equipment malfunction, but in tsunami station configurations, the primary DCP records both 1 and 6 minute averaged water level values, and the backup DCP records 6-minute and 15-second averaged water level data which can be accessed following an event for modeling applications. The backup transducer may also be used to record extreme high water level events, which may exceed the height of the acoustic sensor.   In FY2015, NOAA will begin the transition of the primary water level sensor from acoustic to microwave technology, the first fully non-contact sensor technology to be deployed in the NWLON. As with past sensor technology transitions, substantial test and evaluation was conducted on the new technology and at least one year of overlapping data collection and analysis will be performed at each station to ensure no discontinuities are introduced into the long term sea level records.

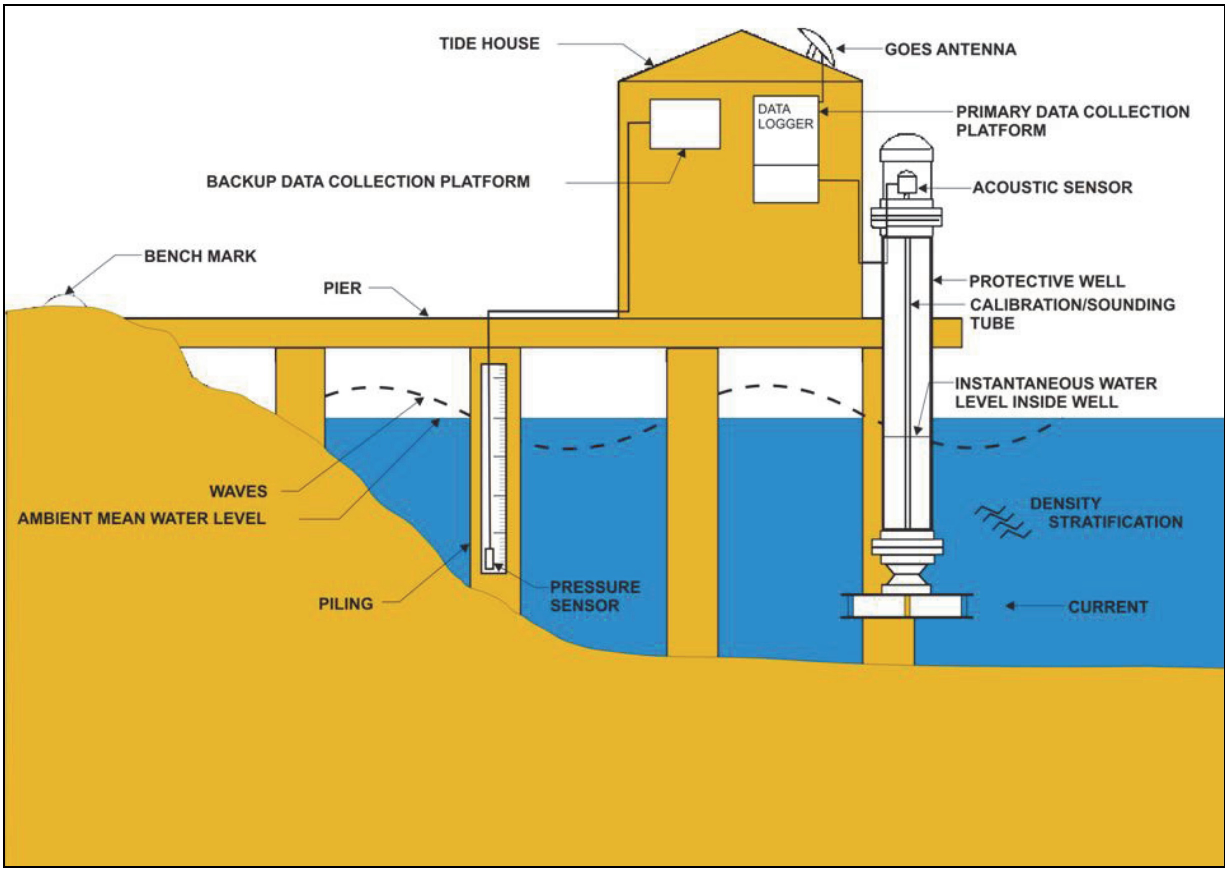


Figure A3 -1. One common NWLON station configuration including acoustic and pressure water level sensors with a primary and backup DCP. (NOAA, 2001)