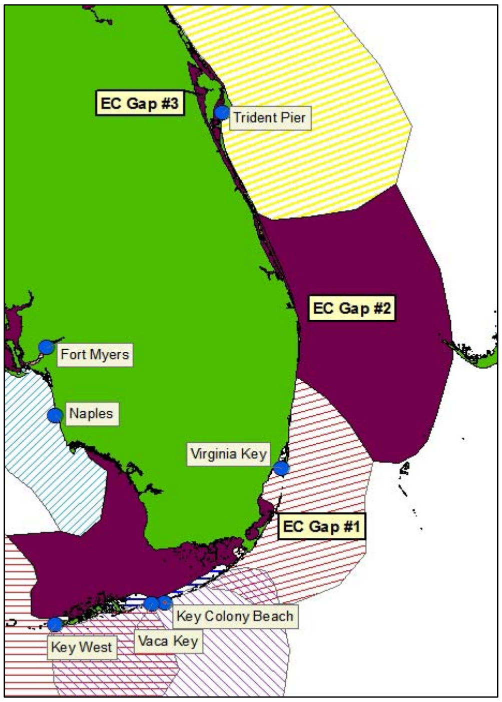
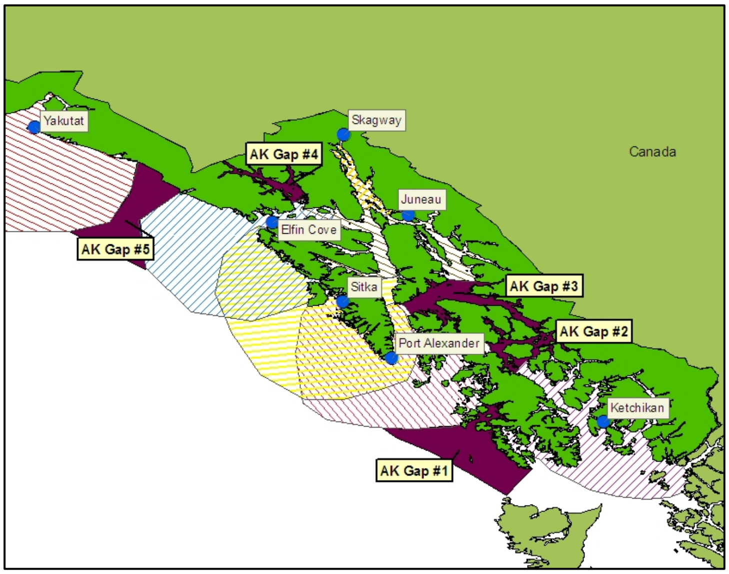
NOAA Technical Memorandum NOS CO-OPS 0048

# A Network Gaps Analysis For The National Water Level Observation Network





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**National Ocean Service**
**Center for Operational Oceanographic Products and Services**

## Center for Operational Oceanographic Products and Services
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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, horizontal sensors and quick response real time buoys. 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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# A Network Gaps Analysis For The National Water Level Observation Network

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National Oceanic and Atmospheric Administration

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# A NETWORK GAPS ANALYSIS FOR THE NATIONAL WATER LEVEL OBSERVATION NETWORK

## PURPOSE

The purpose of this report is to provide a deterministic assessment of the size and geospatial density of water level stations for the National Water Level Observation Network (NWLON). 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.

## 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 Program (NWLP) to meet NOAA's present and future mission requirements for national tide and water level data. The NWLP 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 NWLP 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 NWLP network design is a blend of long-term National Water Level Observation Network (NWLON) 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 WLON coverage using a quantified error analyses approach to identify the gaps.

## NETWORK DESIGN

The requirements of the NWLP 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

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
Layer 7) Climate Change, 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 7). The NWLON is supplemented by short-term station 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 Program. 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) and Tsunami Warning Centers (TWC's). CO-OPS established the Coastal Oceanographic Applications and Services to Tides and Lakes (COASTAL) program to deliver tailored products to the non-navigation community (Layer 6) such as the need for habitat restoration and planning and for environmental monitoring. CO-OPS maintains a set of long-term remote ocean island stations and key shore stations that contribute to the Global Sea Level Observing System (GLOSS) and works in partnership with the NOAA Climate Program Office to enhance products and services for climate monitoring and research (Layer 7) and to integrate our long-term data sets with geodesy to support determination of global sea level change.

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## 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 NWLP 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 information. Together, these long-term and short-term stations and the derived products comprise a tidal datum reference system for the nation. Appendix 2 provides information on the physical configuration of an NWLON station.

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.

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, as the cotidal lines for the open ocean have not yet been mapped with sufficient precision. These remote regions will be covered in a subsequent report. Requirements for these stations are highly driven by climate needs (monitoring global climate oscillations such as 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. 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 (Coordinating Committee, 1995).

Appendix 1 shows the location of the 200 NWLON stations as of 2007. An analysis of gaps in the Great Lakes portion of the NWLON will be presented in a subsequent report. The question becomes "What is the distribution and number of NWLON stations required to provide continuous and overlapping coverage of the coast?" 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.

This 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 -7 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. However, unavoidable losses sometimes occur when stations are destroyed when in the eye-paths of hurricanes or damaged by nor'easters.

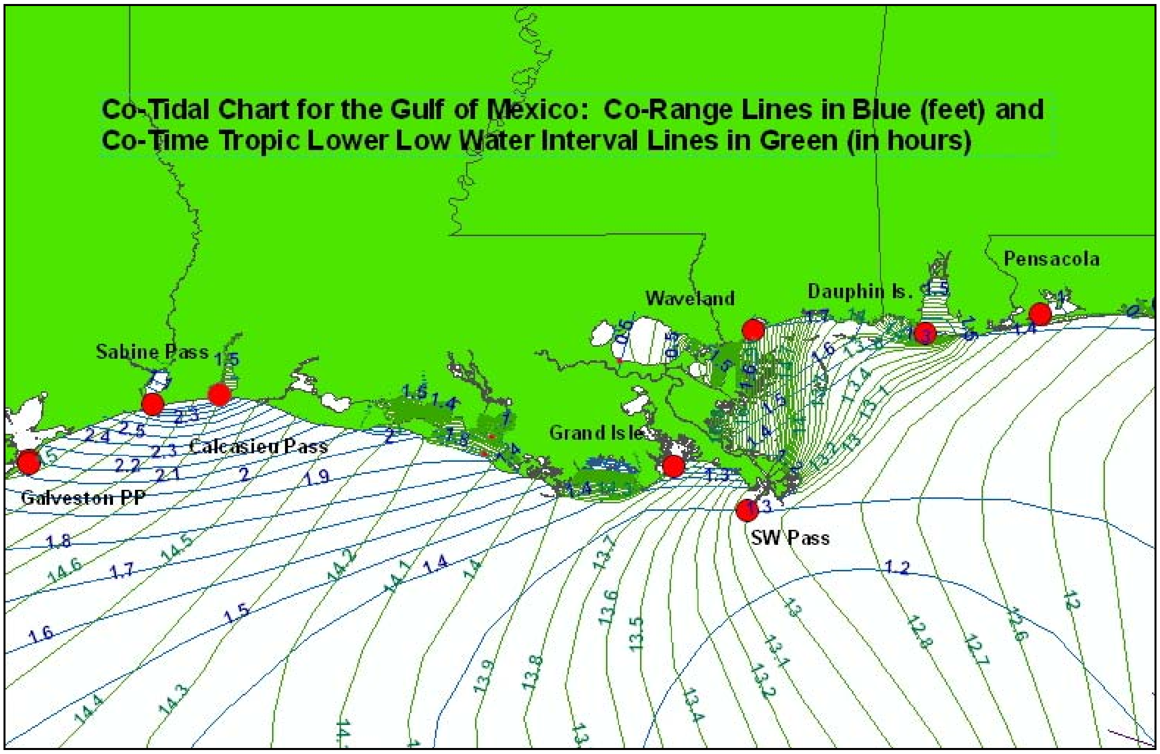

**Figure 1.** The cotidal lines for Diurnal Range (GT) and Tropic Lower Low Water Interval (TcLLWI) in the Gulf of Mexico.

## Layer 2) Relative Mean Sea Level Trends

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 a particular region, if the sea level trends change significantly, then the extrapolation of the tidal datums 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. One example of this variation is in Louisiana (see Figure 2) 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 (Figure 3). 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.

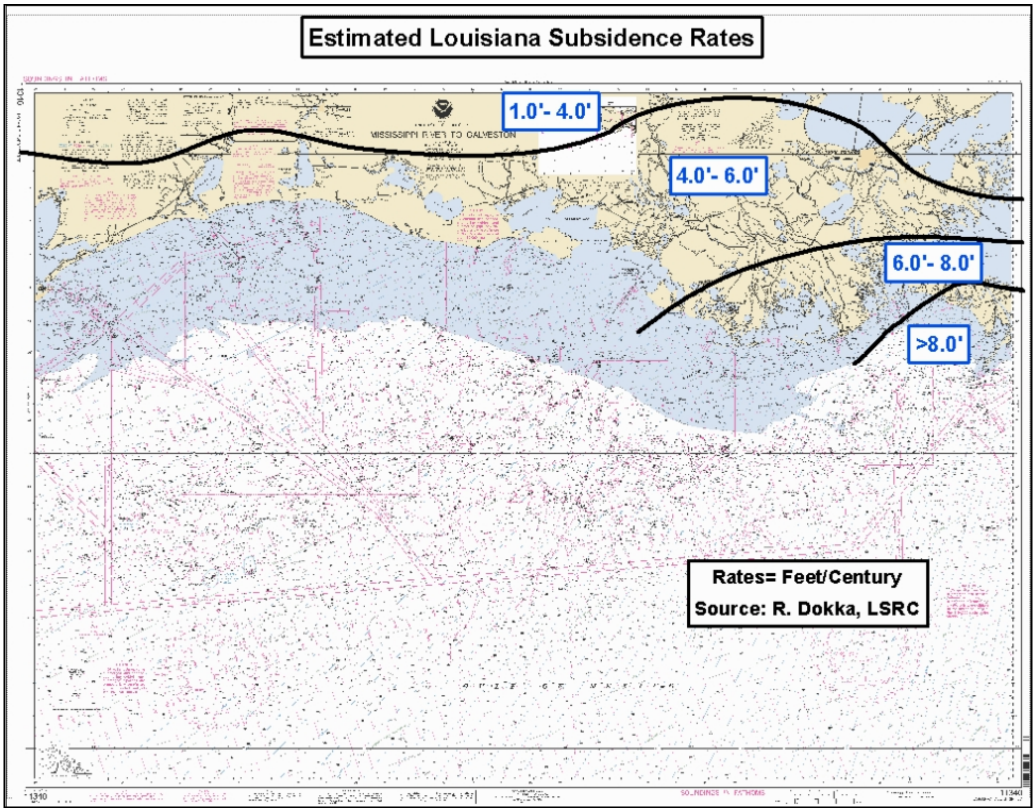

**Figure 2.** Estimated contours for subsidence in Louisiana.

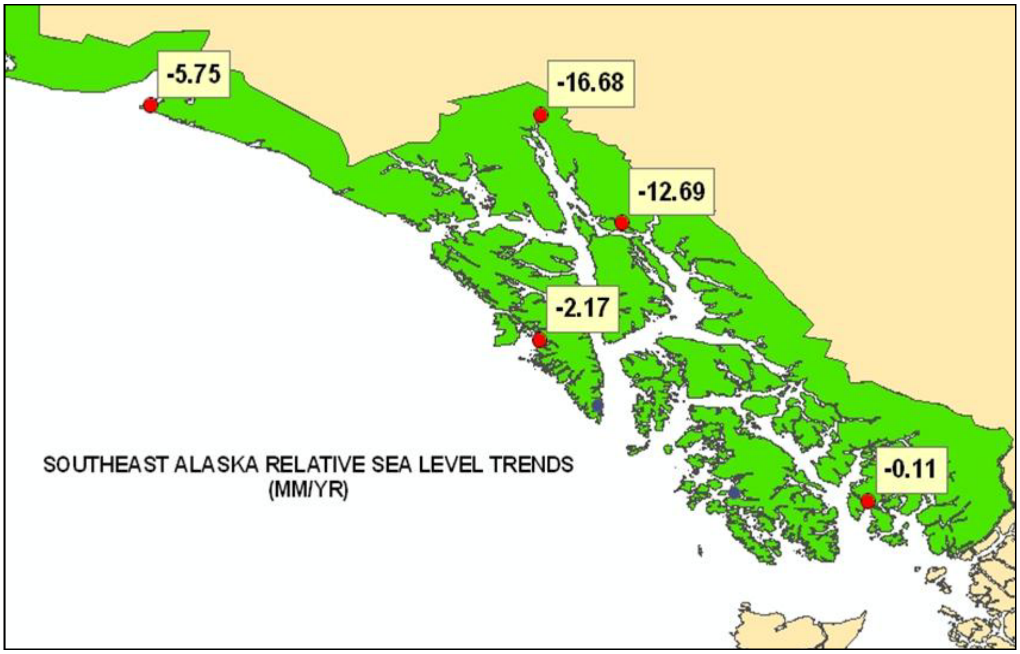

**Figure 3.** Relative mean sea level trends at NWLON stations in Southeast Alaska.

## ROLE OF ERROR BUDGETS

The density of 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 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. There are other important considerations necessary for specific project implementation 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 uncertainties need to be on the order of 0.10 ft. for the error budget to be within desired surveying specifications. The 0.10 ft. is driven by marine boundary and coastal engineering applications and other applications, such has hydrography that have less stringent needs. The NWLP strives for the highest accuracy because of the multiple applications.

The estimates of relative sea level trends found in Zervas (2001) 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. For marine boundary purposes and delineation of the location of the mean high water line, the surveying user community desires known elevation points to the 0.10 ft. uncertainty. This is because a very slight slope in the beach or water front surface will result in a boundary line location 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 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.

## 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 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. Bodnar also developed formulas for Mean High Water (MHW). For purposes of this study, the formulas for Mean Low Water were adopted for use because the low water differences express the effects of shallow water and bottom friction better than MHW.

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

$$\mathrm{S1M} = 0.0068\ \mathrm{ADLWI} + 0.0053\ \mathrm{SRGDIST} + 0.0302\ \mathrm{MNR} + 0.029$$

$$\mathrm{S3M} = 0.0043\ \mathrm{ADLWI} + 0.0036\ \mathrm{SRGDIST} + 0.0255\ \mathrm{MNR} + 0.029$$

$$\mathrm{S6M} = 0.0019\ \mathrm{ADLWI} + 0.0023\ \mathrm{SRGDIST} + 0.0207\ \mathrm{MNR} + 0.030$$

$$\mathrm{S12M} = 0.0045\ \mathrm{SRSMN} + 0.128\ \mathrm{MNR} + 0.025$$

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 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 purposes of this NWLON study, the target value of datum uncertainty of 0.12 ft (95% confidence interval) has been selected for determination of the extent of coverage for datum determination for each NWLON station. This target value 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. 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 and for outside users such as the US Army Corps of Engineers.

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 (Allstations), which also provides latitude and longitude information. The Allstations 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. Geographic distance is estimated using the GIS measure tool.

The basic equation being used in the spreadsheet calculation is:

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

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 0.29 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 Gulf Coast tide stations the tides are predominantly diurnal (one high tide and one low tide per day). 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.

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.

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 | DIST | SQRDIST | Sub. Range | MNR | S3M | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | hrs. | n. miles | | | ratio | 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 |

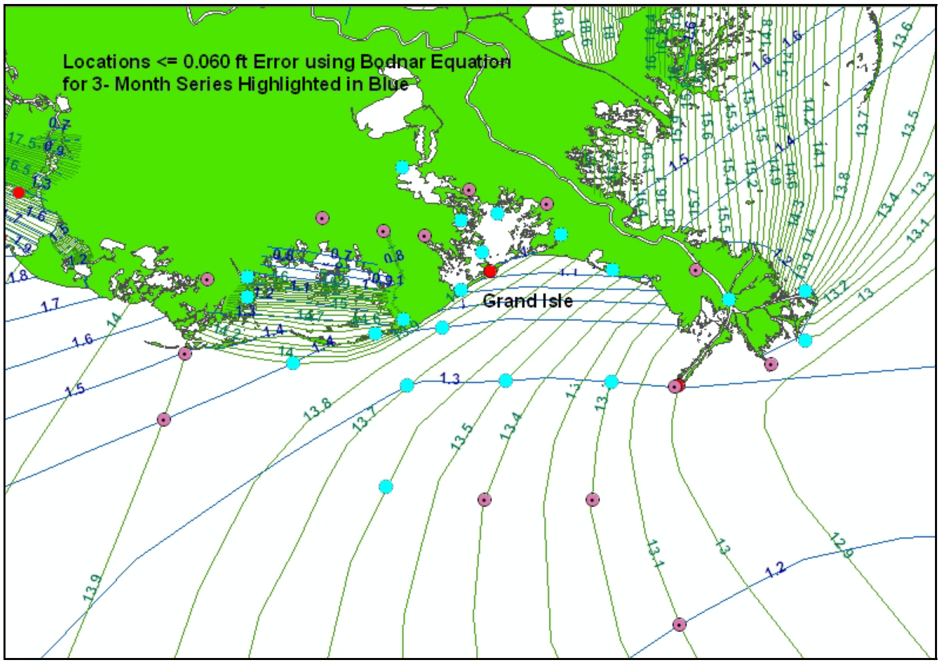

**Figure 4.** The locations of the historical tide stations and offshore points used in the Bodnar equation analysis for Grand Isle. The locations within the 0.060 ft. cutoff are highlighted in blue.

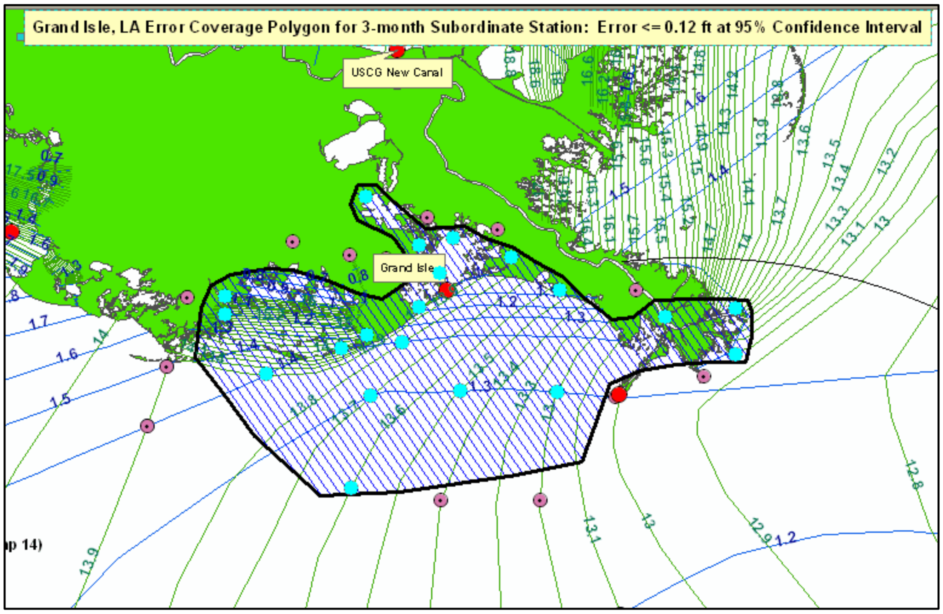

**Figure 5.** The GIS error polygon for Grand Isle, Louisiana depicting the geographic area of coverage for datum determination at short-term tide station.

Figure 6 below, shows the polygon analysis for other stations in the region near Grand Isle. The overlap and the lack of overlap in coverage polygons is readily apparent. This analysis has been repeated around the U.S. coastline, excluding the remote pacific ocean islands and the U.S. Great Lakes.

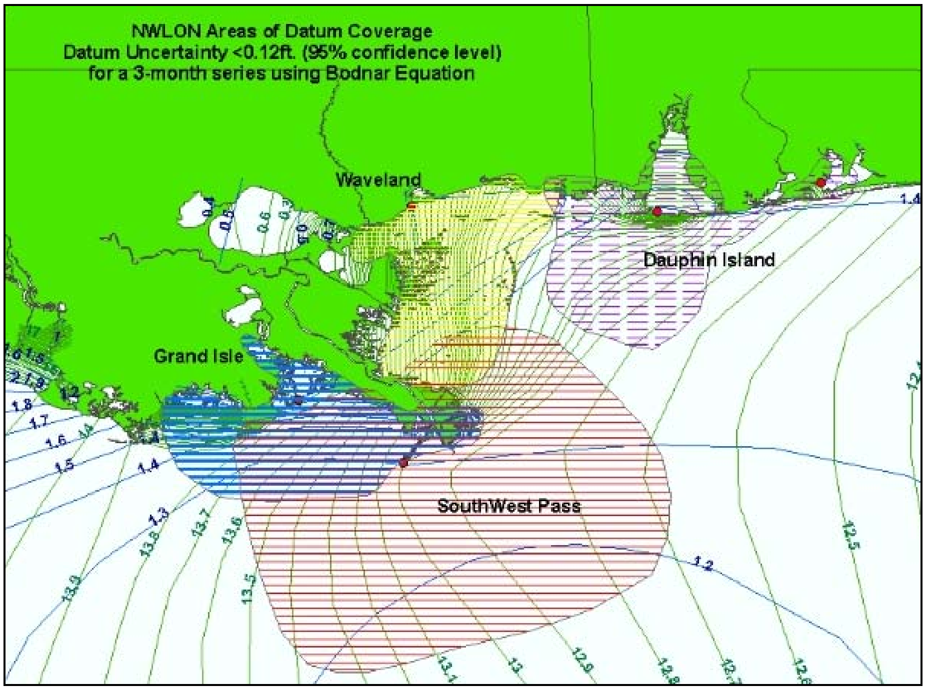

**Figure 6.** Example of the GIS analysis results for nearby stations.

## 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, those assumptions are an over simplification in areas with extremely fasting changing tidal characteristics become extremely complicated within small distances. Examples are 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 where 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 RESULTS

### East Coast

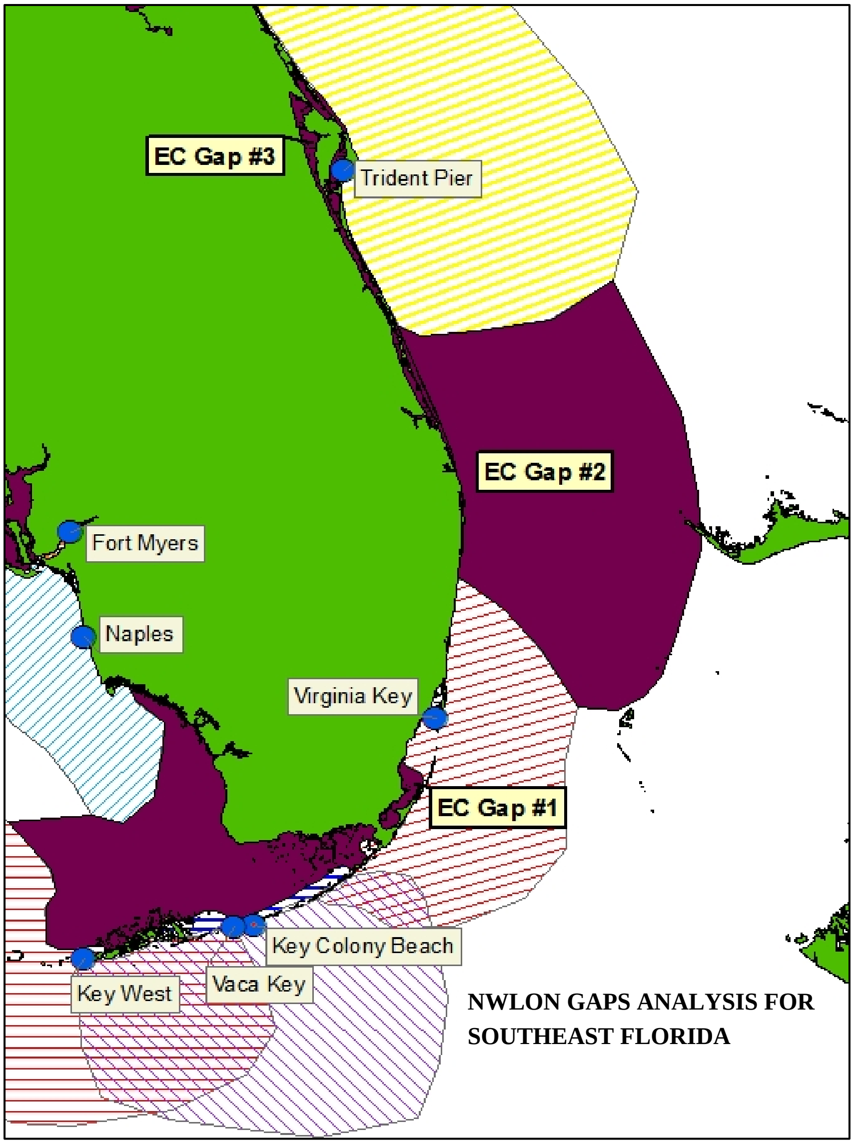

**Figure 7.** NWLON gaps analysis for southeast Florida.

1) Southern Biscayne Bay
2) Outer Coast, Vicinity of Lakeworth and North Palm Beach, FL: There is difficulty in maintaining a station in this gap. Former long-term stations at Lakeworth, Haulover Pier, and Miami Beach Pier were all destroyed by storms or construction.
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.

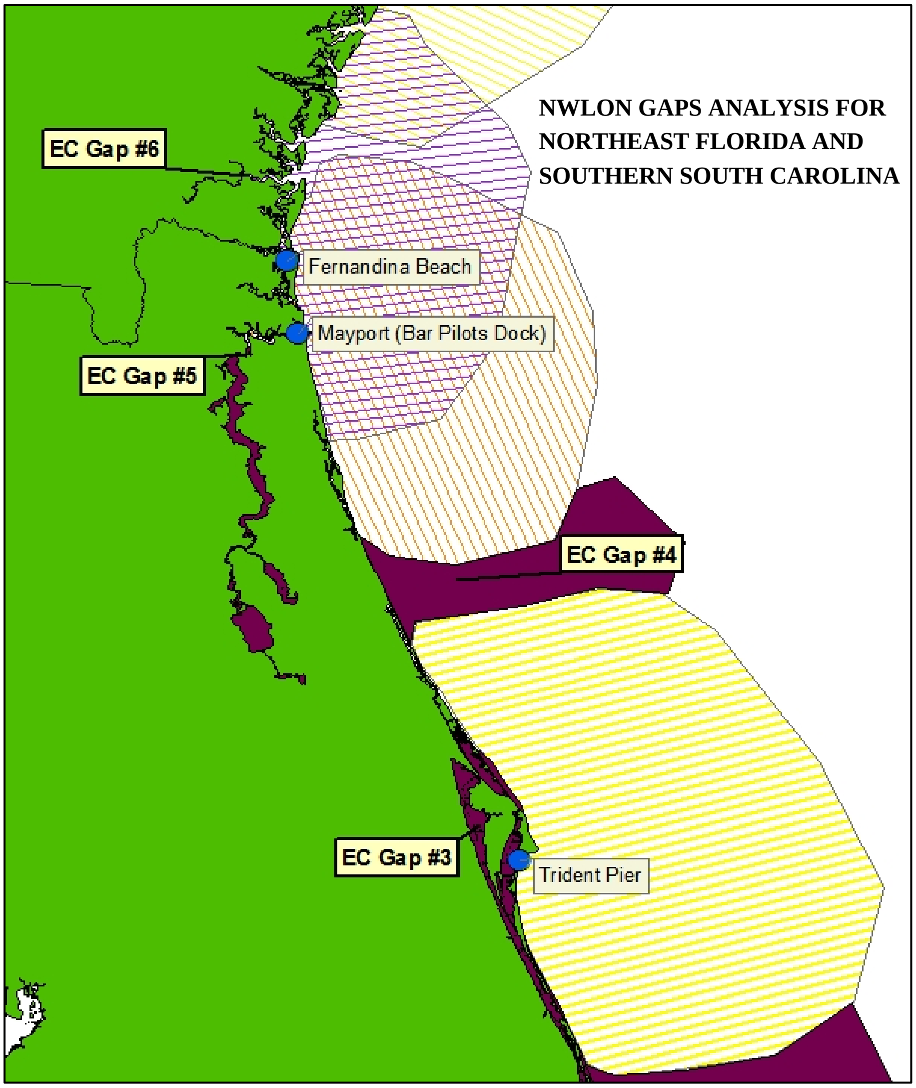

**Figure 8.** NWLON gaps analysis for northeast Florida and southern South Carolina.

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

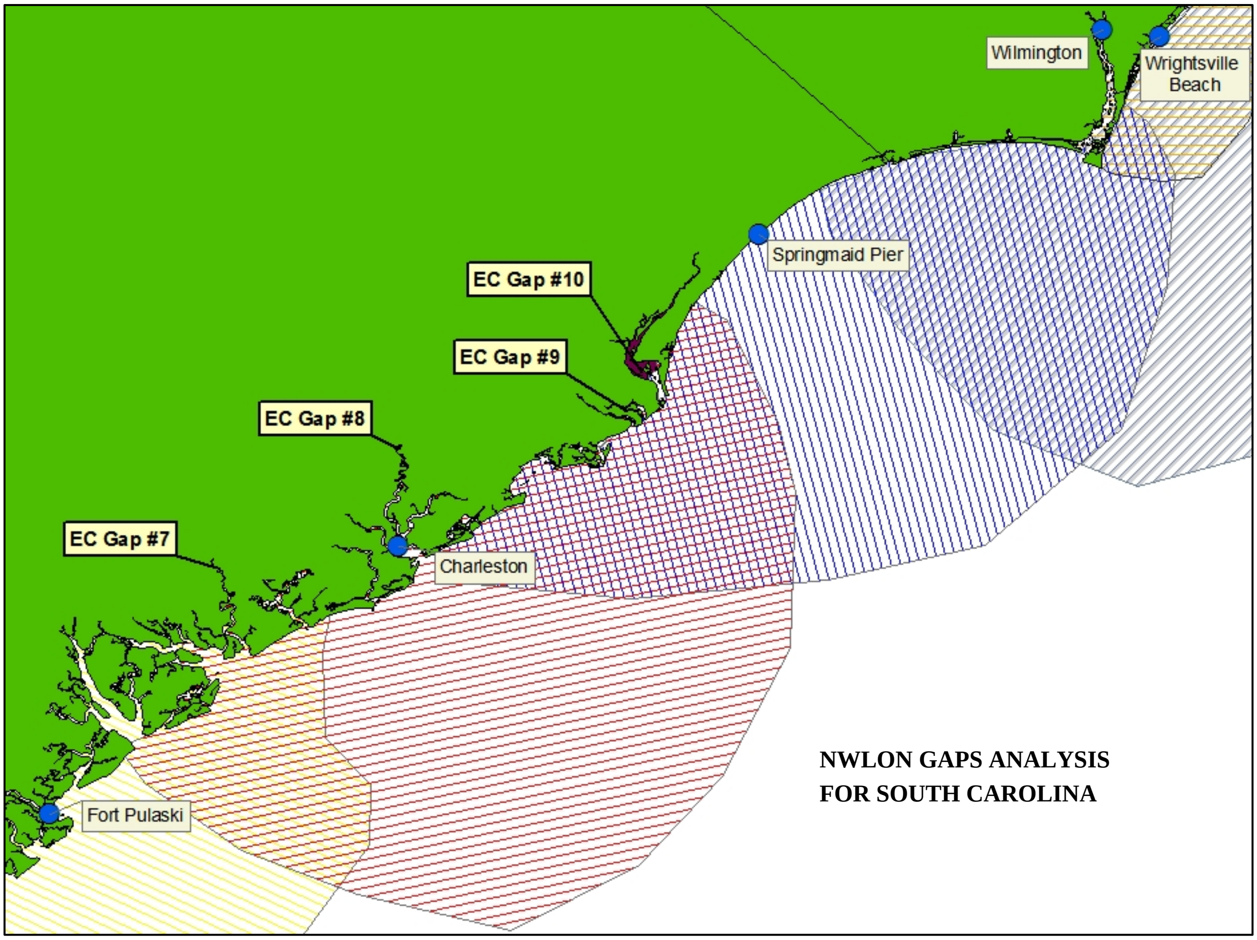

**Figure 9.** NWLON gaps analysis for South Carolina.

7) Upper Edisto River, SC
8) Upper Cooper River, SC
9) South Santee River, SC
10) Winyah Bay, SC

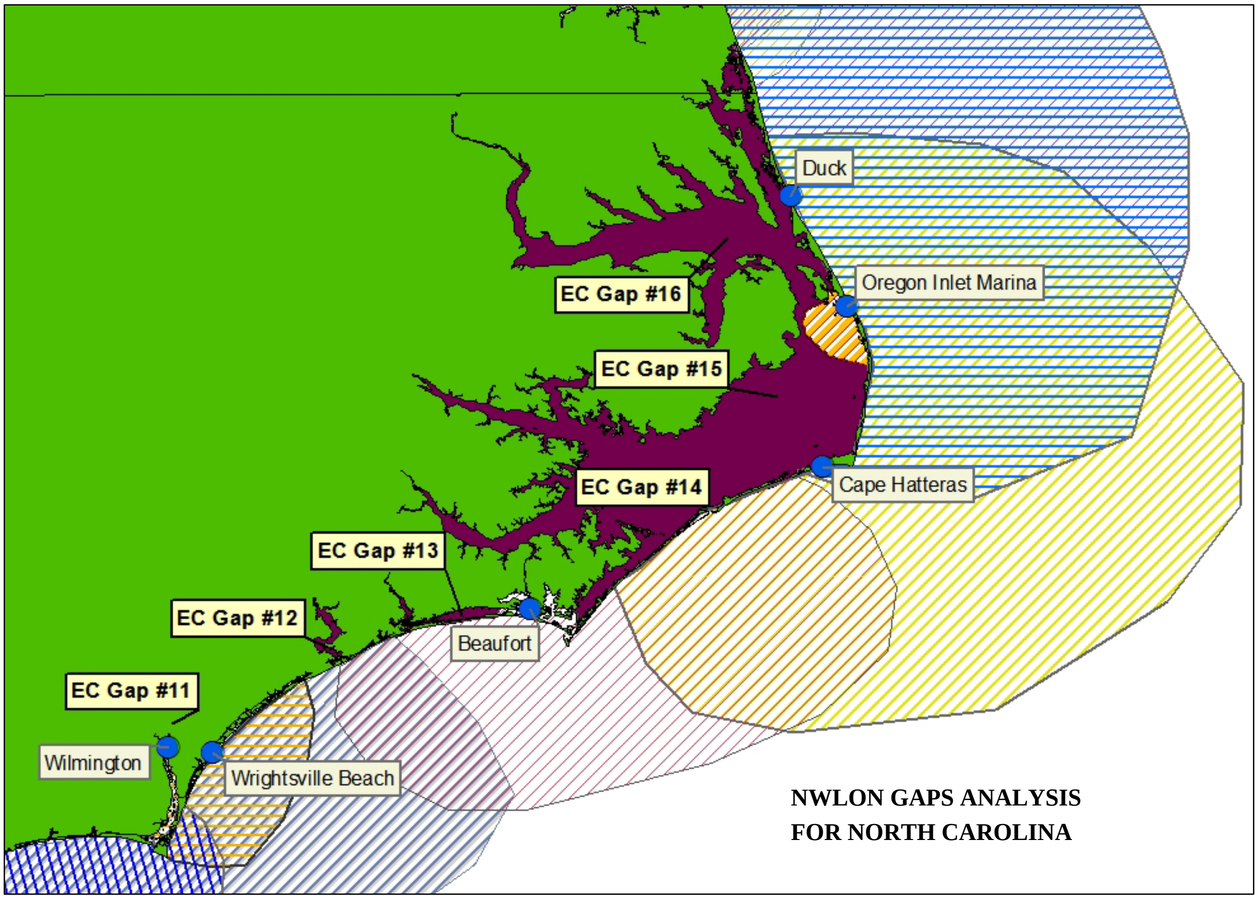

**Figure 10.** NWLON gaps analysis for North Carolina.

11) Upper Cape Fear River, NC
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 though 16 represent areas of transition from tidal on the outer coast to non-tidal in the inner bays.

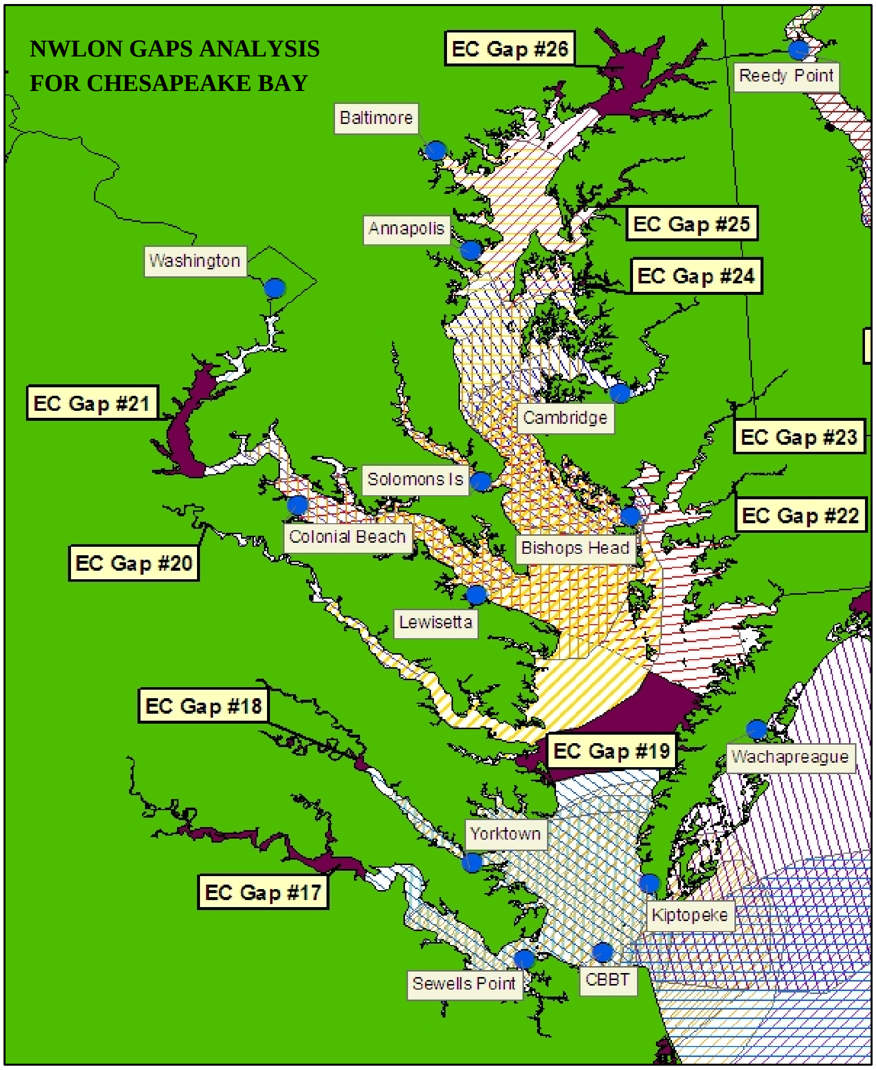

**Figure 11.** NWLON gaps analysis for the Chesapeake Bay.

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) Potomac River, MD/VA
22) Upper Wicomico River, MD
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.

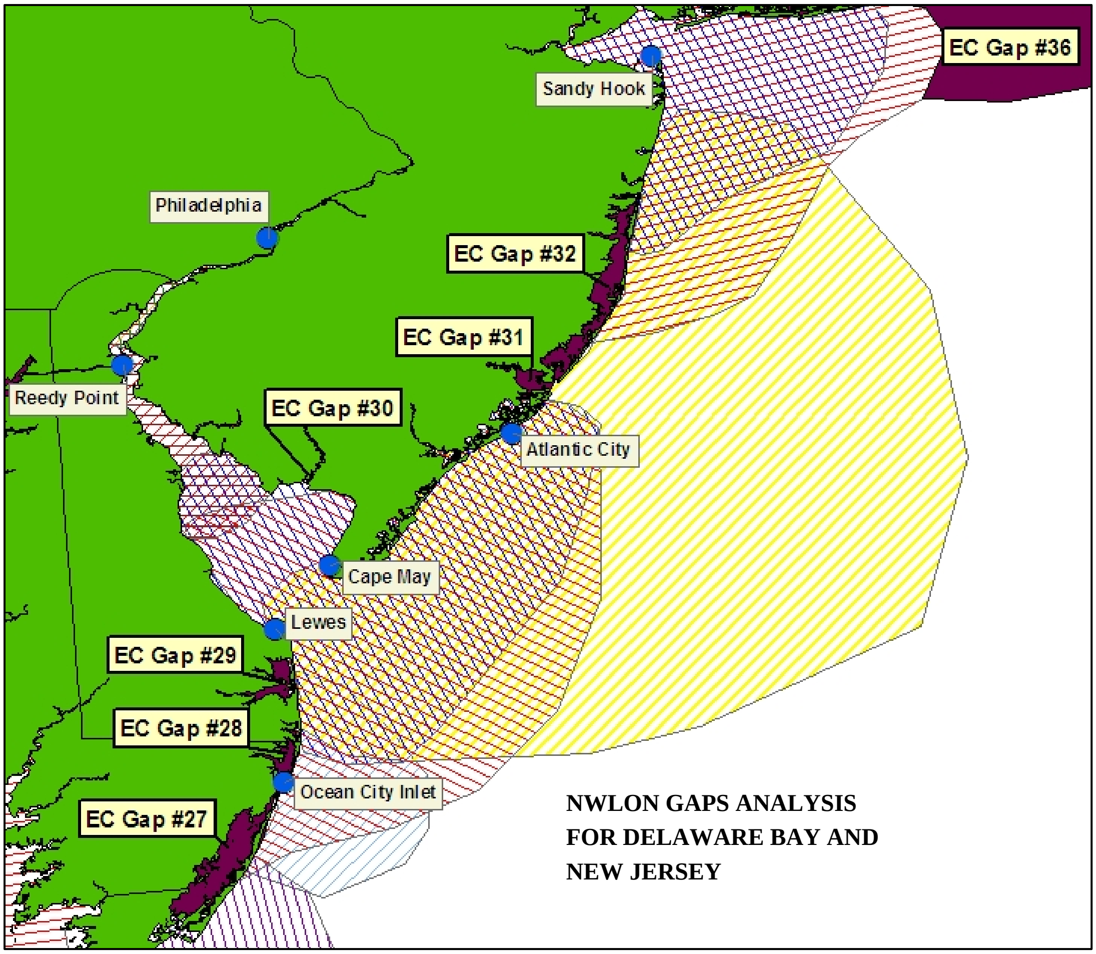

**Figure 12.** NWLON gaps analysis for Delaware Bay and New Jersey.

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

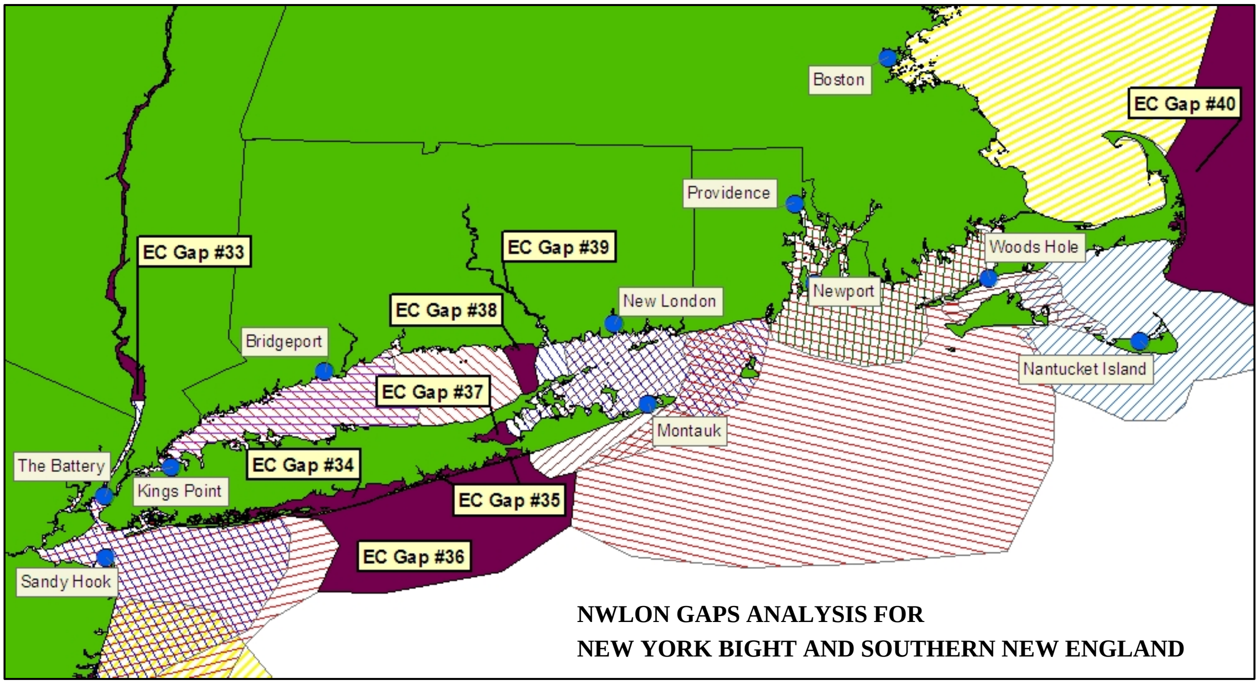

**Figure 13.** NWLON gaps analysis for New York and southern New England.

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

Note: EC gaps 36 and 40 are problematic to try to establish new stations due to the high energy beaches and lack of existing infrastructure in the form of ocean piers.

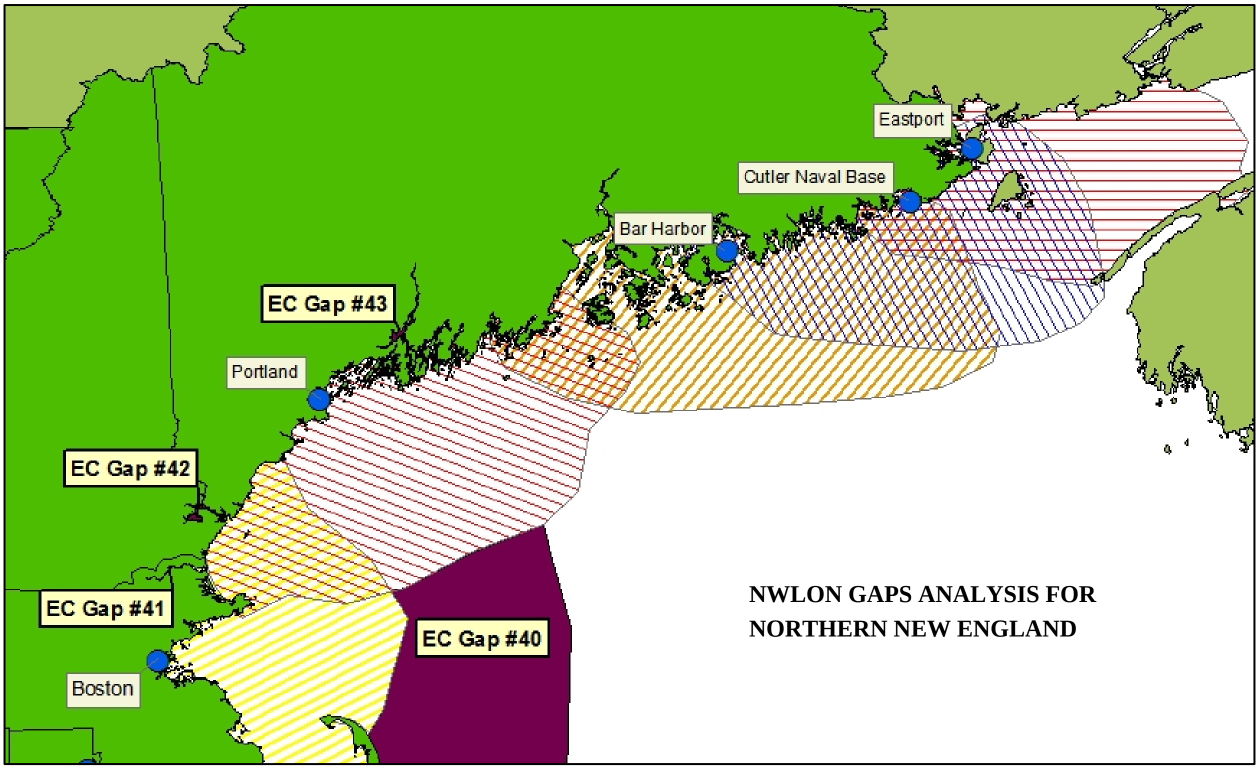

**Figure 14.** NWLON gaps analysis for northern New England.

41) Upper Merrimack River
42) Vicinity of Bellamy River, NH
43) Upper Kennebec River, ME

## Caribbean

The gaps analysis for the Caribbean (Figure 13) shows that with the addition of the recent NWLON station 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.

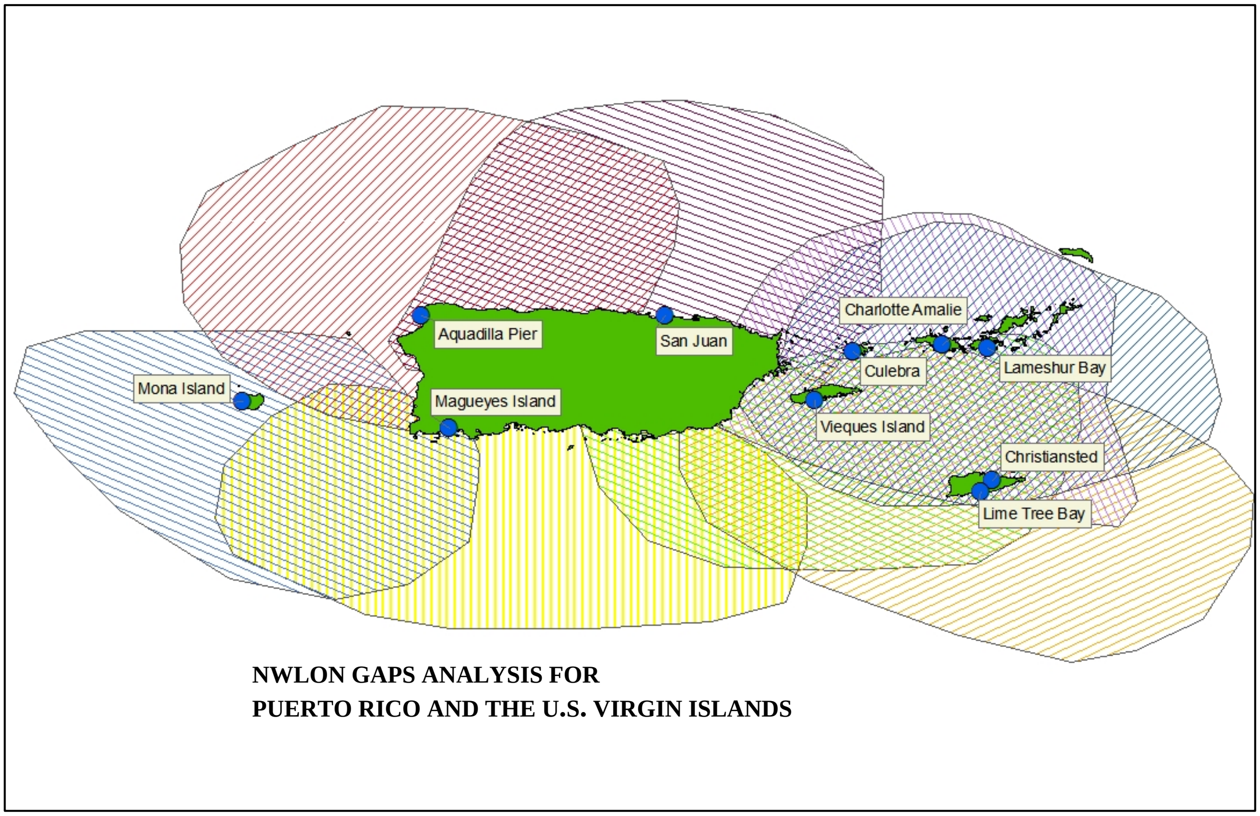

**Figure 15.**  NWLON gaps analysis for the Caribbean exhibiting no existing gaps in coverage.

## Gulf Coast

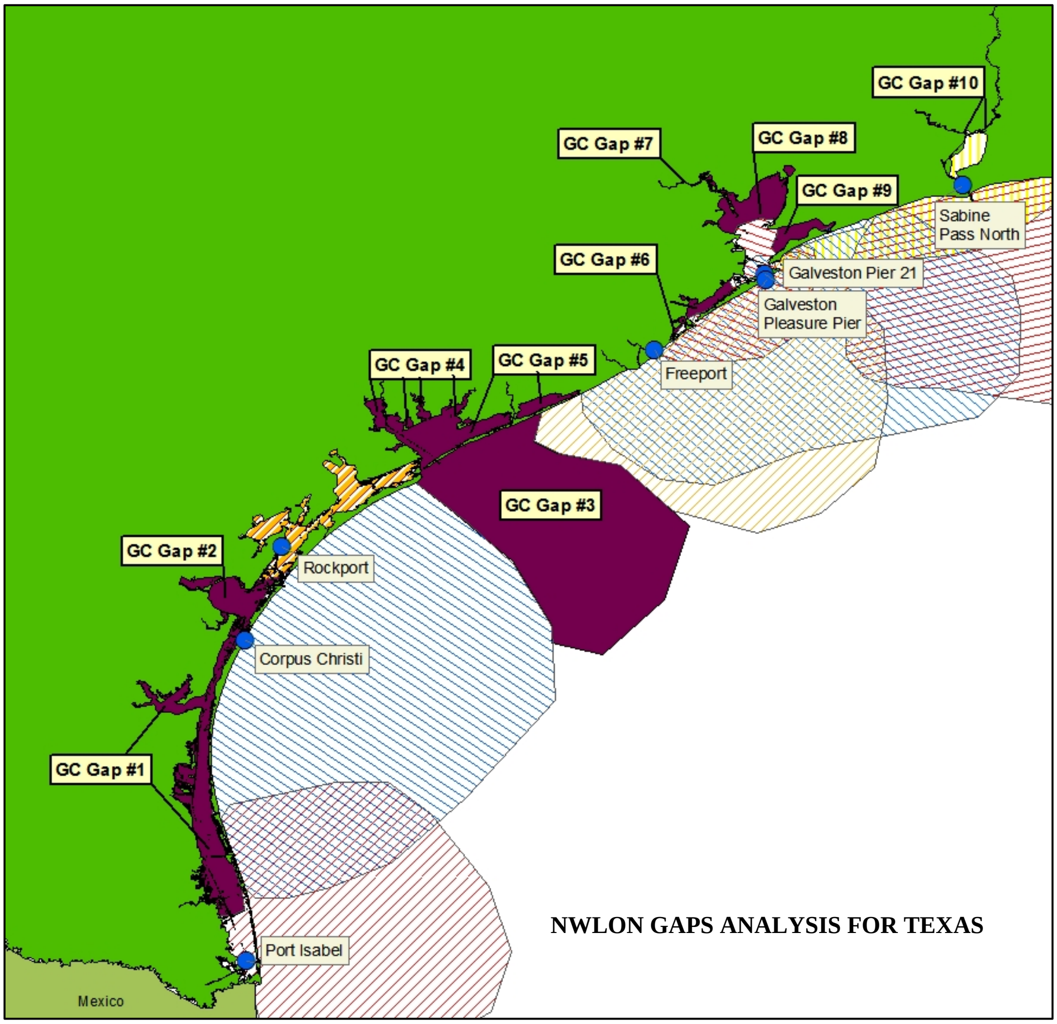

**Figure 16.** NWLON gaps analysis for Texas.

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

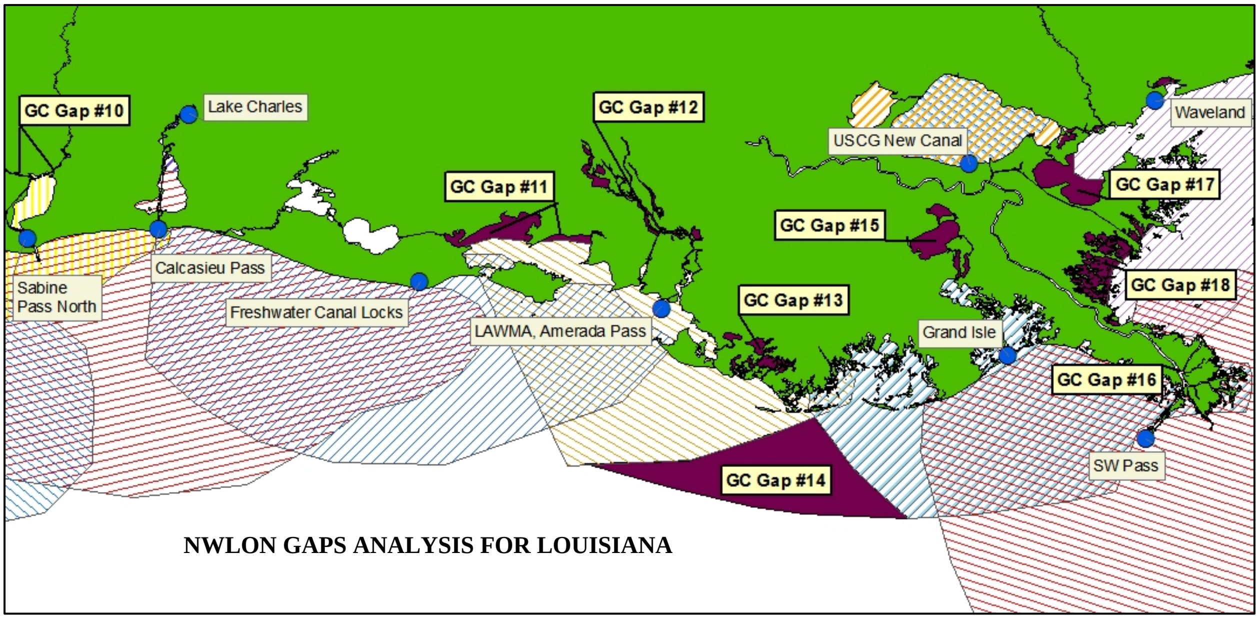

**Figure 17.** NWLON gaps analysis for Louisiana.

10) Upper Neches and Sabine Rivers, TX/LA
11) Upper Vermillion and West Cote Blanche Bays, LA
12) Upper Atchafalaya River Region, LA
13) Houma Ship Canal, LA
14) Entrance to Terrebonne Bay, 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) Lake Borgne, LA
18) Western Breton ; Chandeleur Sound. LA

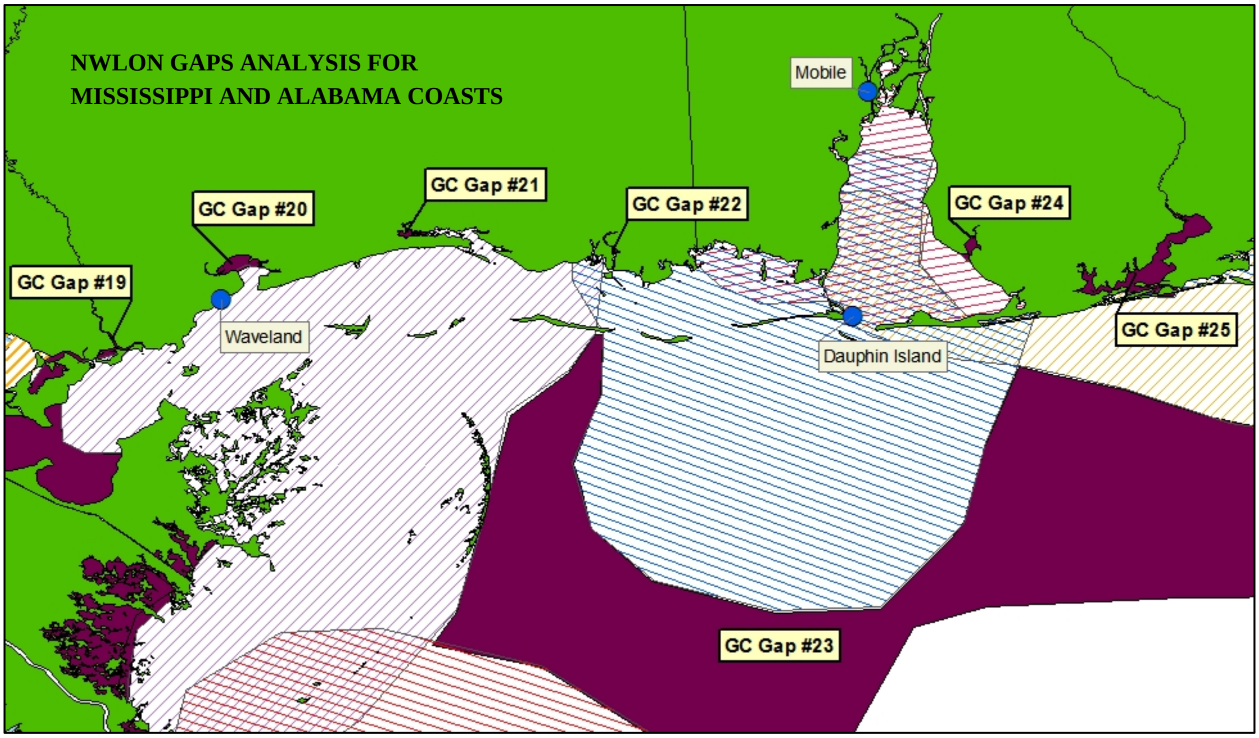

**Figure 18.** NWLON gaps analysis for the Mississippi and Alabama coasts.

19) Lower Pearl River and Vicinity, MS
20) Upper Bay St. Louis, MS
21) Upper Biloxi Bay, MS
22) Pascagoula River, MS
23) Offshore Ocean Springs, Vicinity of Horn Island, MS
24) Weeks Bay, AL
25) Wolf Bay, AL and Perdido Bay, AL/FL

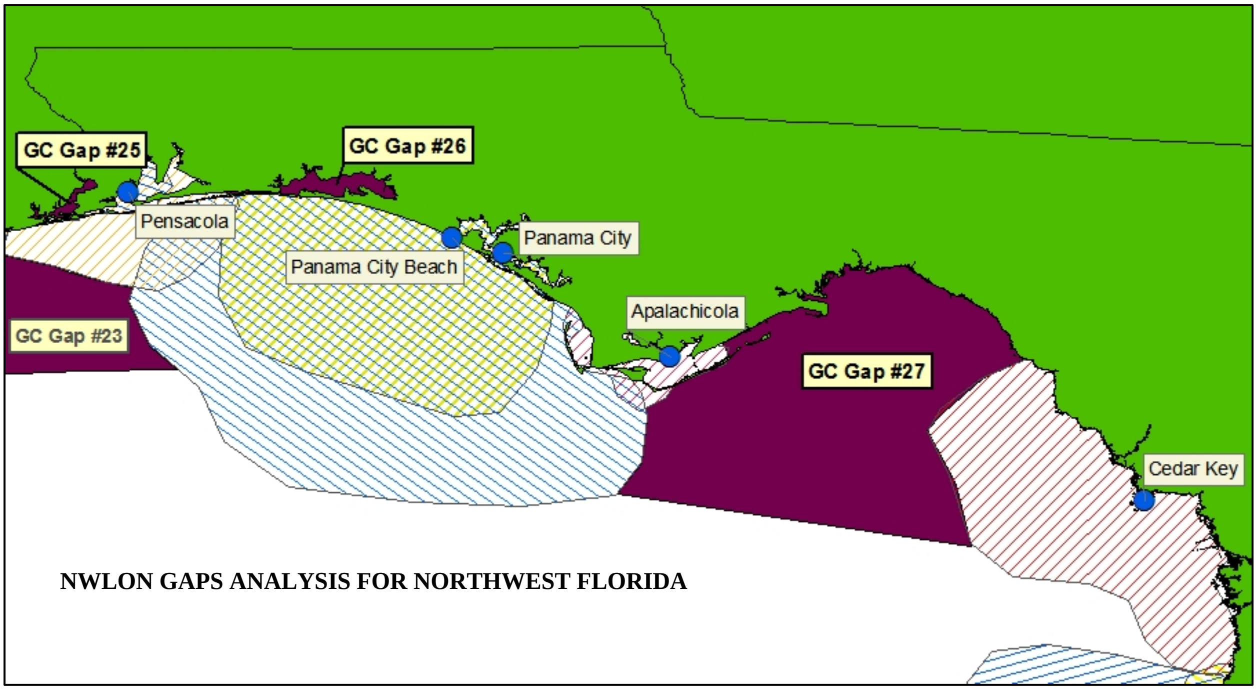

**Figure 19.** NWLON gaps analysis for northwest Florida.

25) Wolf Bay, AL and Perdido Bay, AL/FL
26) Choctawhatchee Bay, FL
27) Apalachee Bay, St. George Sound, FL and Vicinity

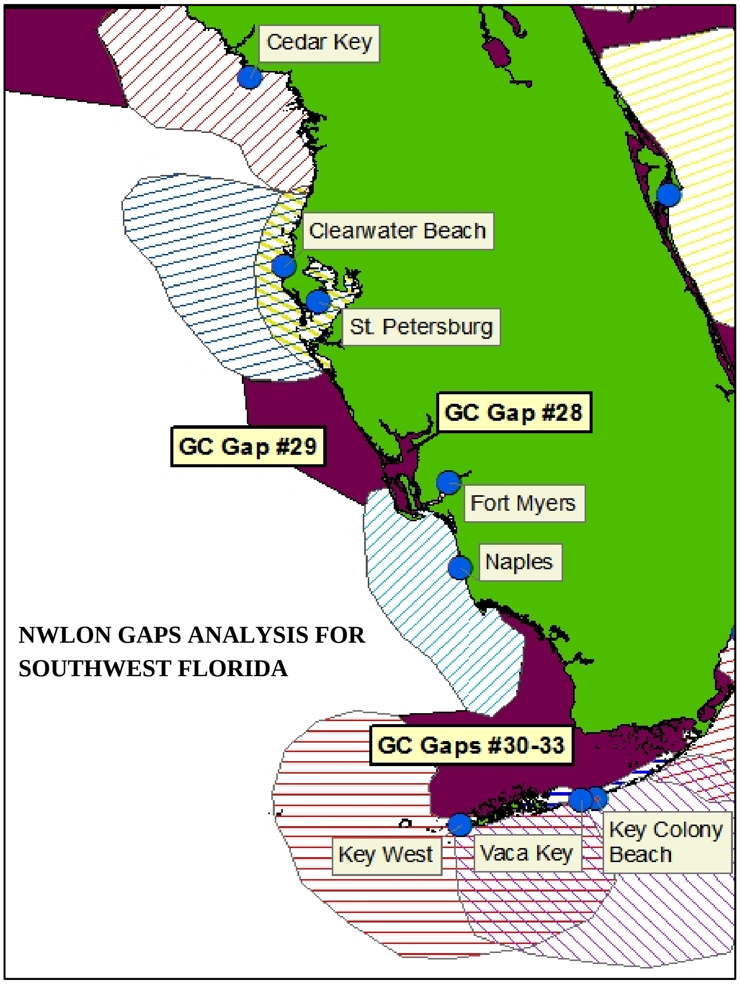

**Figure 20.** NWLON gaps analysis for southwest Florida.

28) Charlotte Harbor, FL
29) Vicinity and Outer Coast of Venice, FL
30) Chokoloskee, FL
31) Cape Sable, FL
32) Lower Keys (Gulf of Mexico side) and Vicinity, FL
33) Northern Florida Bay, FL:  This bay is a region of transition form tidal to non-tidal.

## West Coast

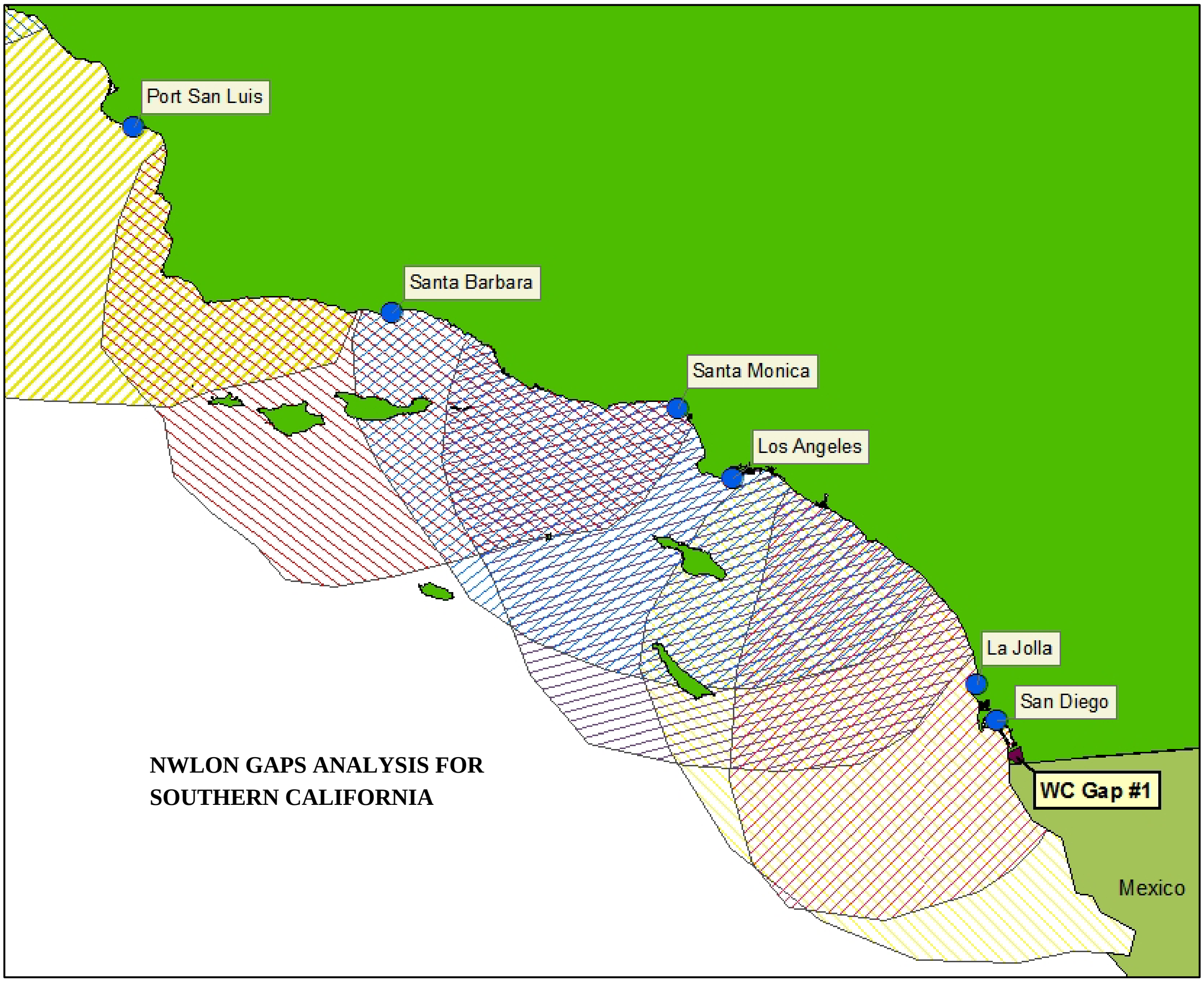

**Figure 21.** NWLON gaps analysis for southern California.

1) Tijuana Slough NERRS, CA

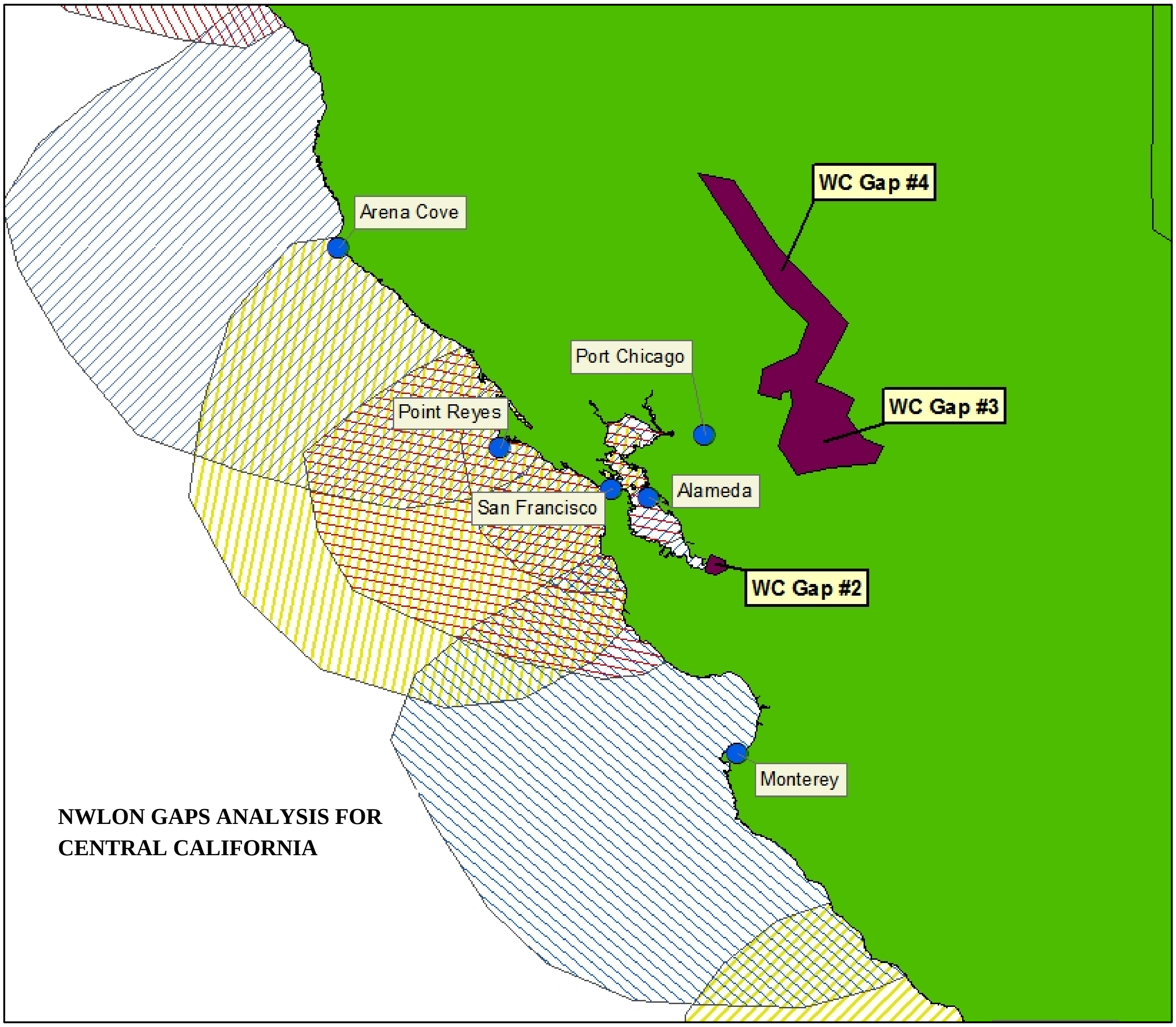

**Figure 22.** NWLON gaps analysis for central California.

2) Southern 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.

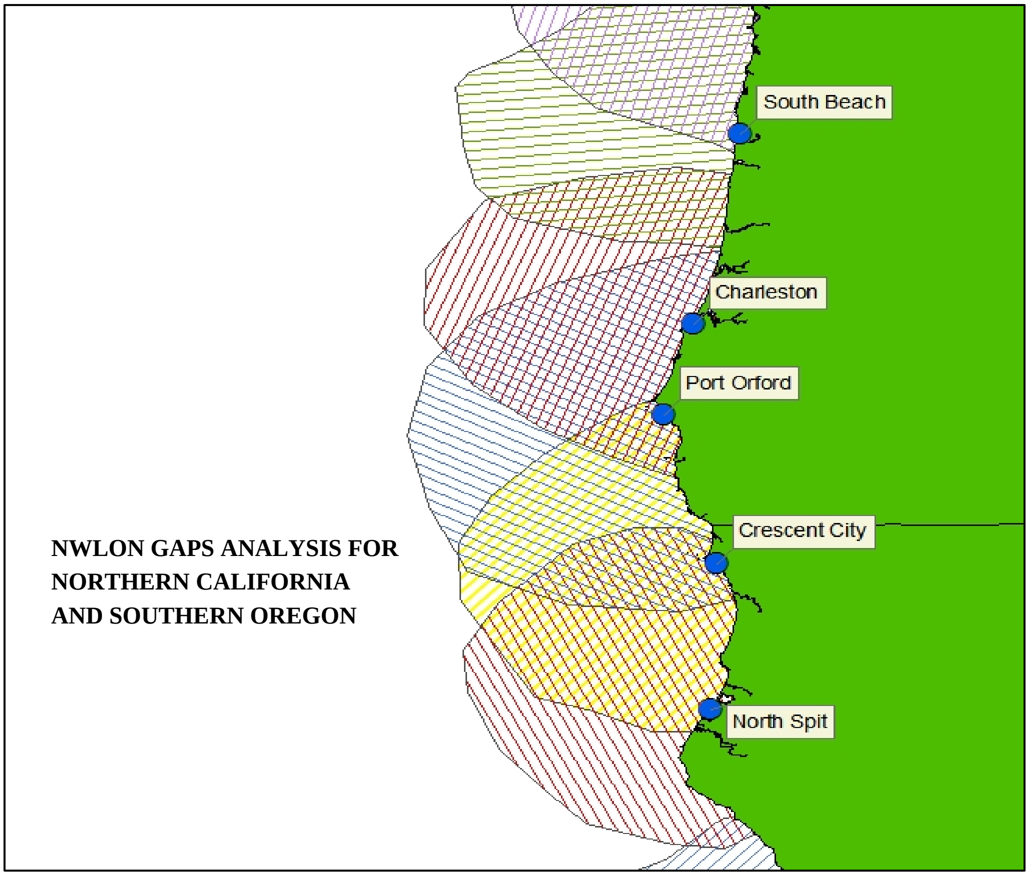

**Figure 23.** NWLON gaps analysis for northern California and southern Oregon exhibiting no existing gaps in coverage.

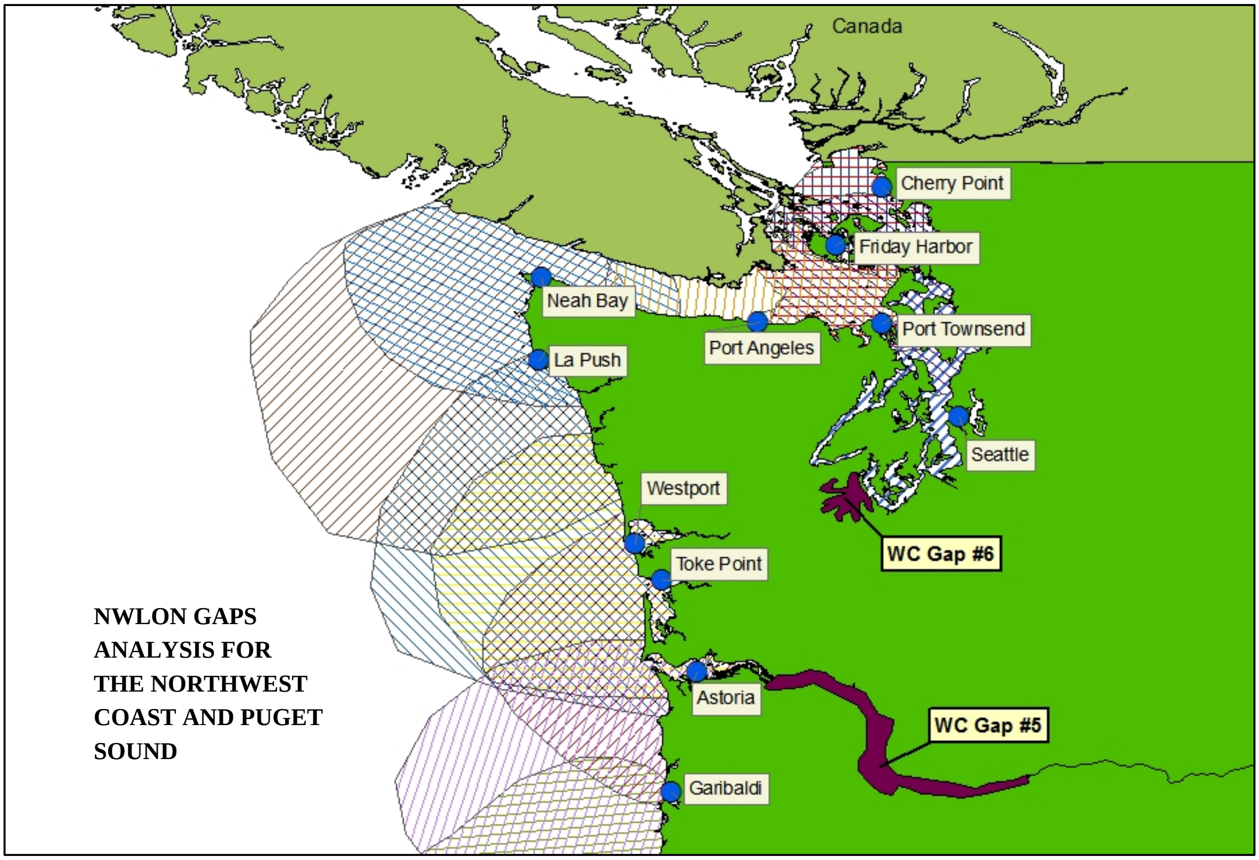

**Figure 24.** NWLON gaps analysis for the northwest coast and Puget Sound.

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)

## Alaska

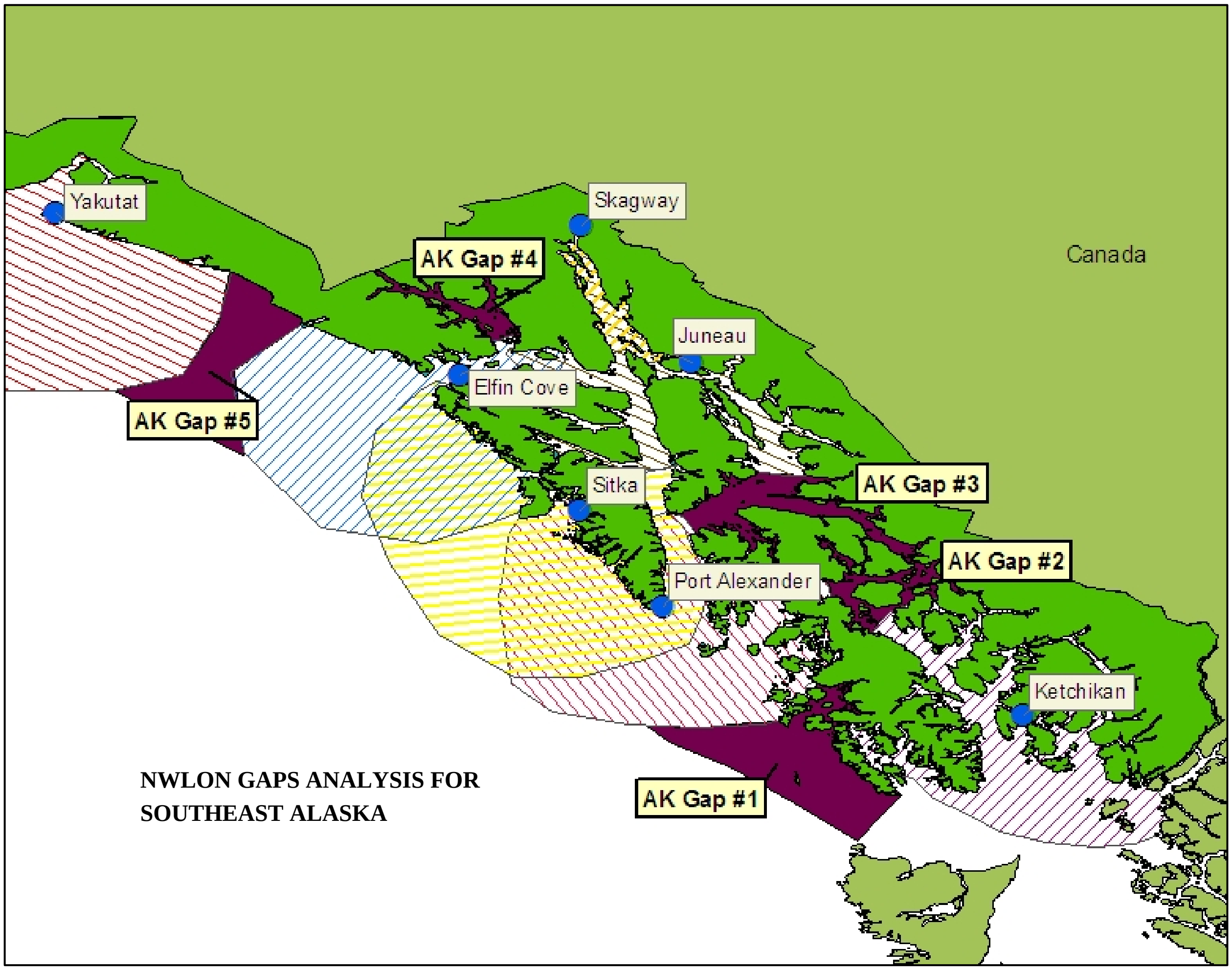

**Figure 25.** NWLON gaps analysis for southeast Alaska.

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.

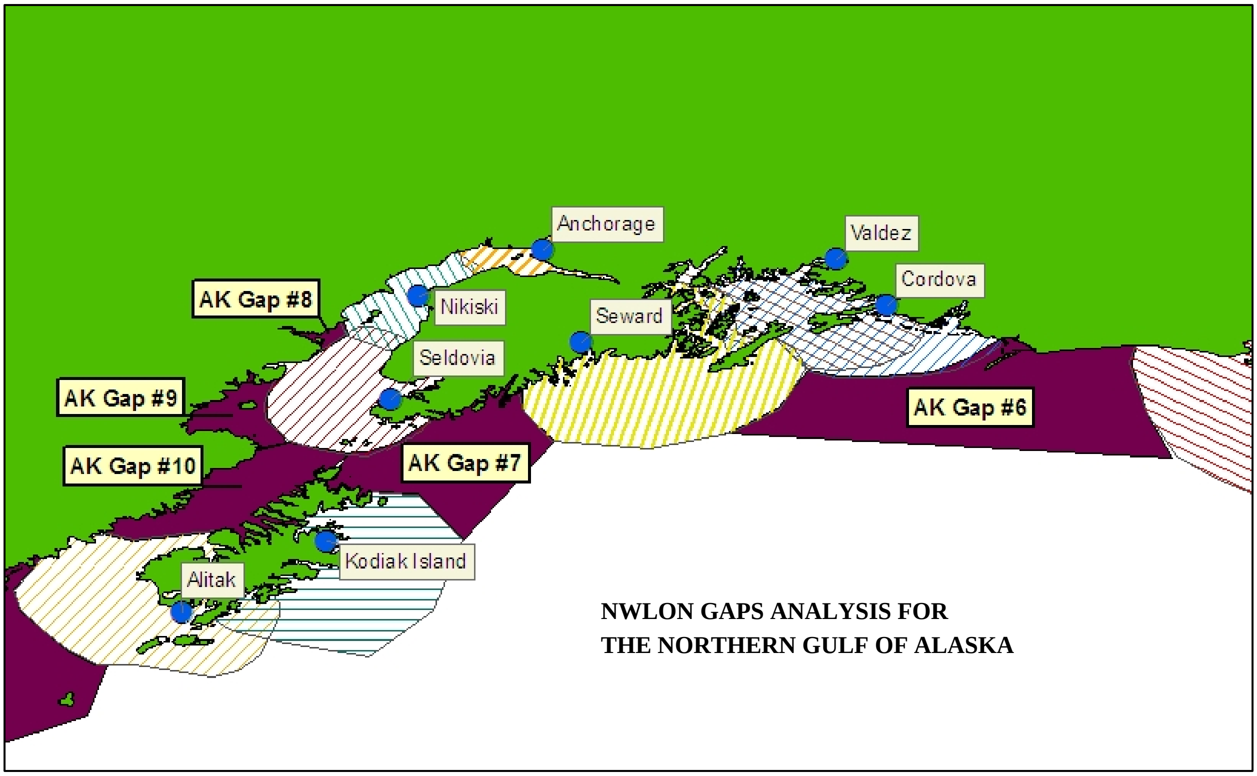

**Figure 26.** NWLON gaps analysis for the northern Gulf of Alaska.

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

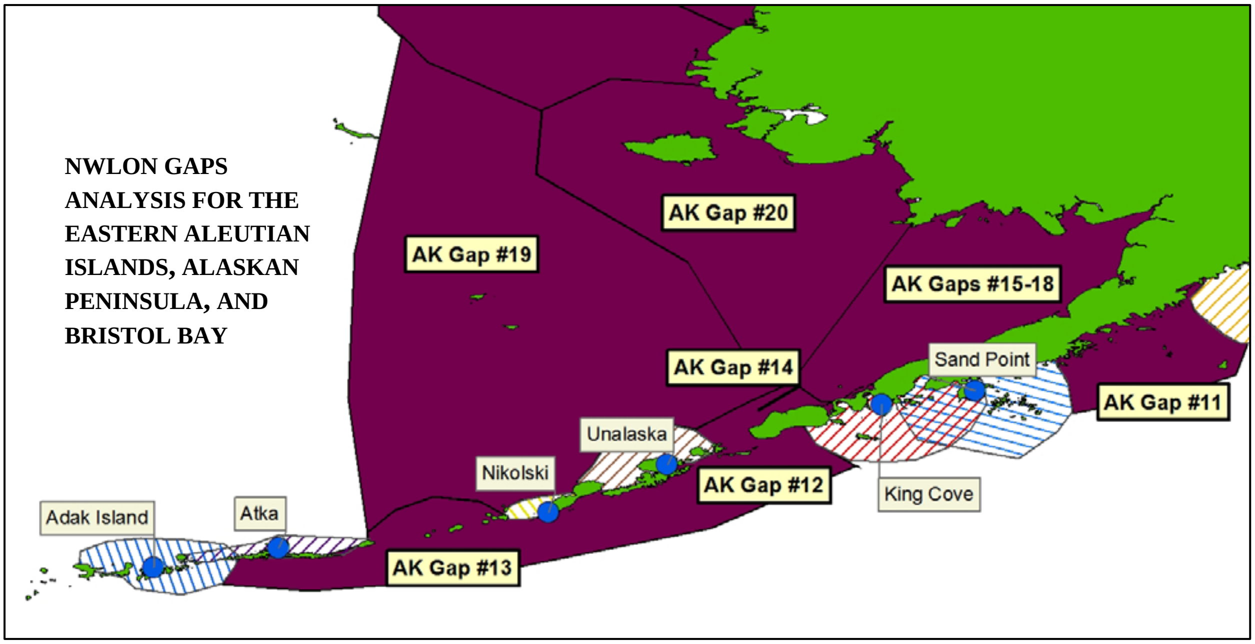

**Figure 27.** NWLON gaps analysis for the eastern Aleutian Islands, Bristol Bay and Alaskan Peninsula.

11) Port Wrangell to Chignik Bay, Alaska Peninsula
12) Aleutian Islands, South Side, Ugamak Strait (Unimak Island) to Unalaska Island
13) Aleutian Islands, South Side, Unalaska Island to Atka Island
14) North Side Unimak Island
15) Port Moller, Bristol Bay
16) Kvichak Bay Vicinity
17) Nushagak Bay
18) Hagemeister Island Vicinity
19) Pribilof Islands and Vicinity
20) Kuskokwim Bay

Not shown in Figure – western Aleutian Islands

21) Amchitka Island
22) Attu Island

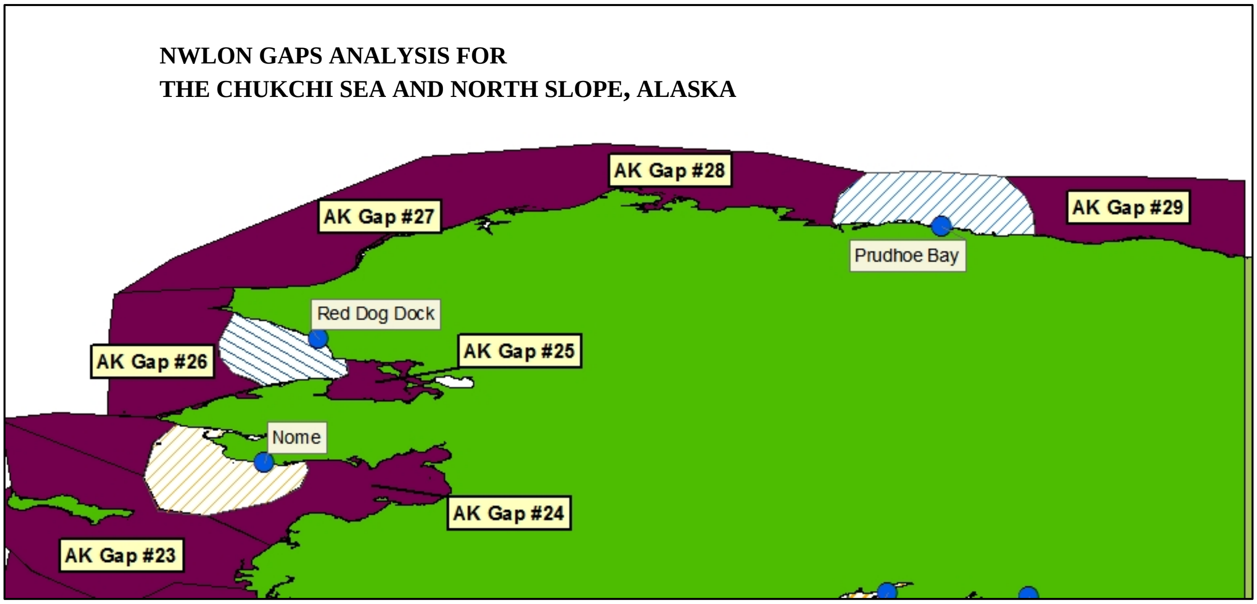

**Figure 28.** NWLON gaps analysis for the Chukchi Sea and North Slope, Alaska.

23) Yukon River Delta
24) Eastern Norton Sound
25) Eastern Kotzebue Sound: This area transitions form tidal to non-tidal.
26) Bering Straits
27) Chukchi Sea, Pt Hope to Pt. Barrow
28) Pt. Barrow to Prudhoe Bay
29) Prudhoe Bay to Canadian Border

## Hawaii

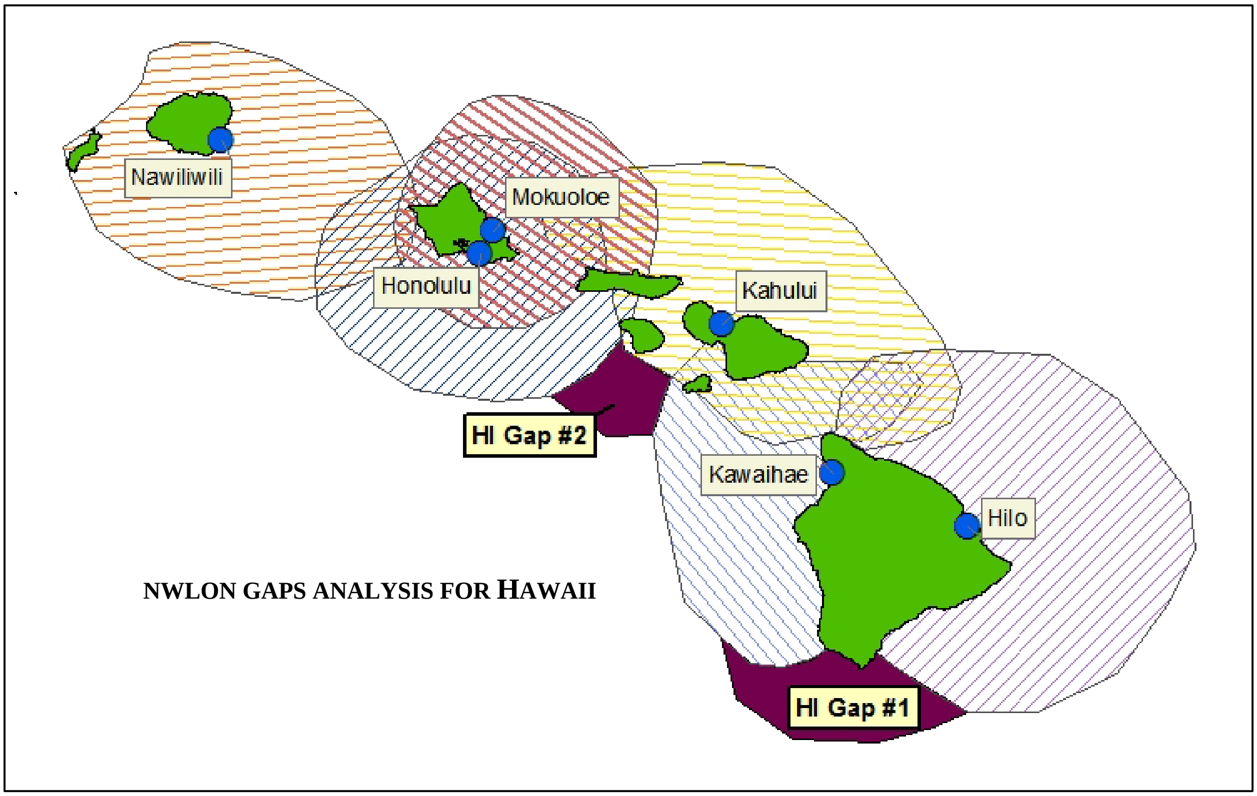

**Figure 29.** NWLON gaps analysis for Hawaii.

1) Southeast Point of Hawaii Island, HA
2) South shore of Kaho O'Lowe Island, HA

## SUMMARY

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 NWLP. 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 can take place. The analysis results identified approximately 113 gaps in NWLON coverage beyond the 200 station deployed as of FY2007. Forty-three (43) gaps are located along the east coast, 33 in the gulf coast, 6 gaps on the west coast, 29 gaps in Alaska, and 2 in Hawaii.

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 will now be 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 will allow for more precise error estimates to be input to the total error budgets for all applications.

The 113 NWLON gaps, added to the existing 200 NWLON stations, results in an approximate target NWLON of 313 stations (excluding any Great Lakes analysis that would identify new stations). As a next step towards adding additional stations to the NWLON, the GIS layers created by this effort will be used to evaluate the locations of other Federal, state, and regional water level observation networks for possible leveraging and partnership opportunities. 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 gaps and CO-OPS will work with them to integrate those stations into the NWLON. Other potential partners include the US Army Corps of Engineers (USACE) and the US Geological Survey (USGS).

## ACKNOWLEDGMENTS

The authors wish to thank Allison Allen and Monica Cisternelli of CO-OPS and former CO-OPS employee, Kelly Stumbaugh, in the compilation of information for this report and appreciate all of the dedication and hard work of CO-OPS and predecessor organization employees that has resulted in a National Water Level Program that continues to serve the nation every day.

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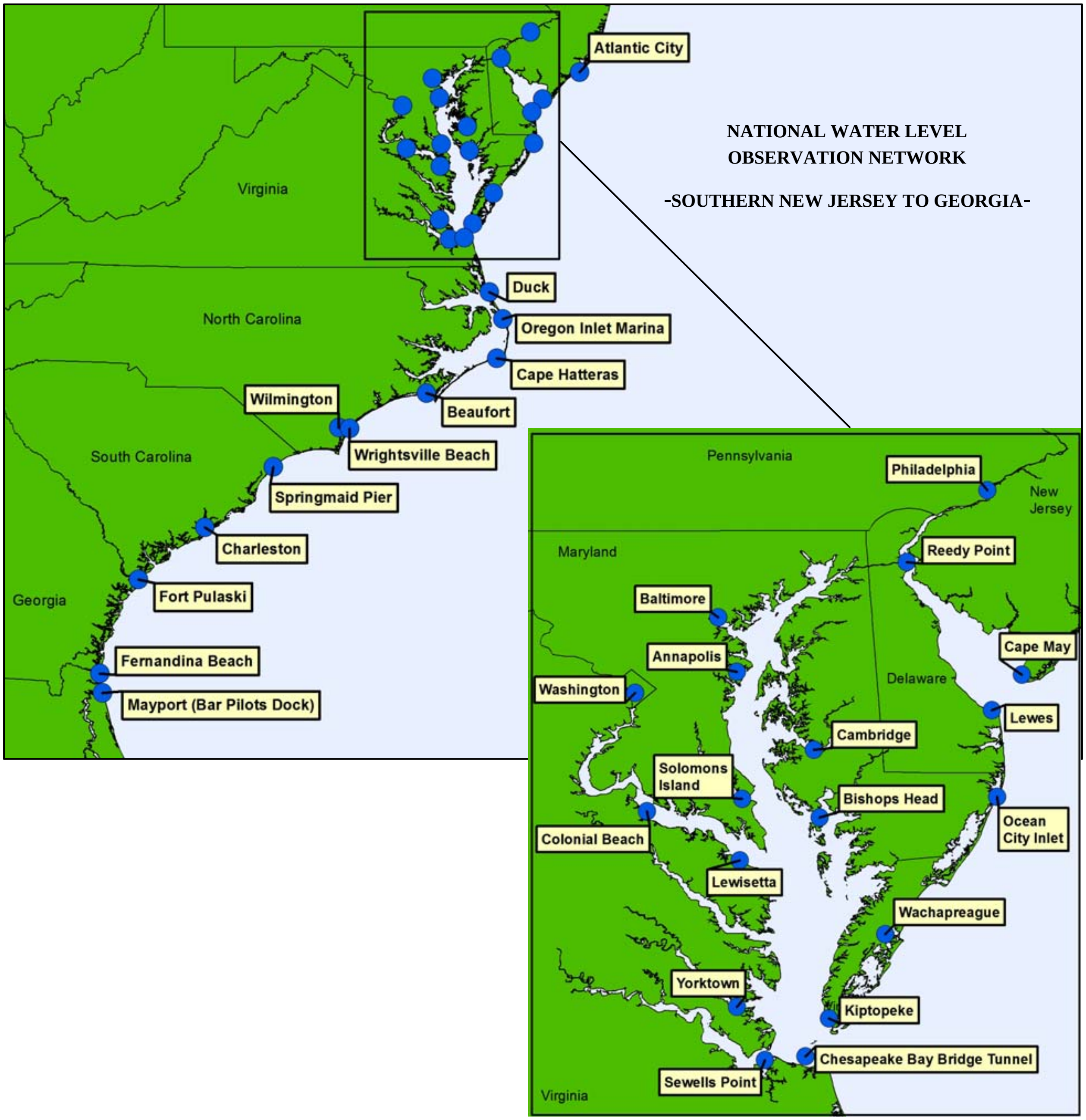
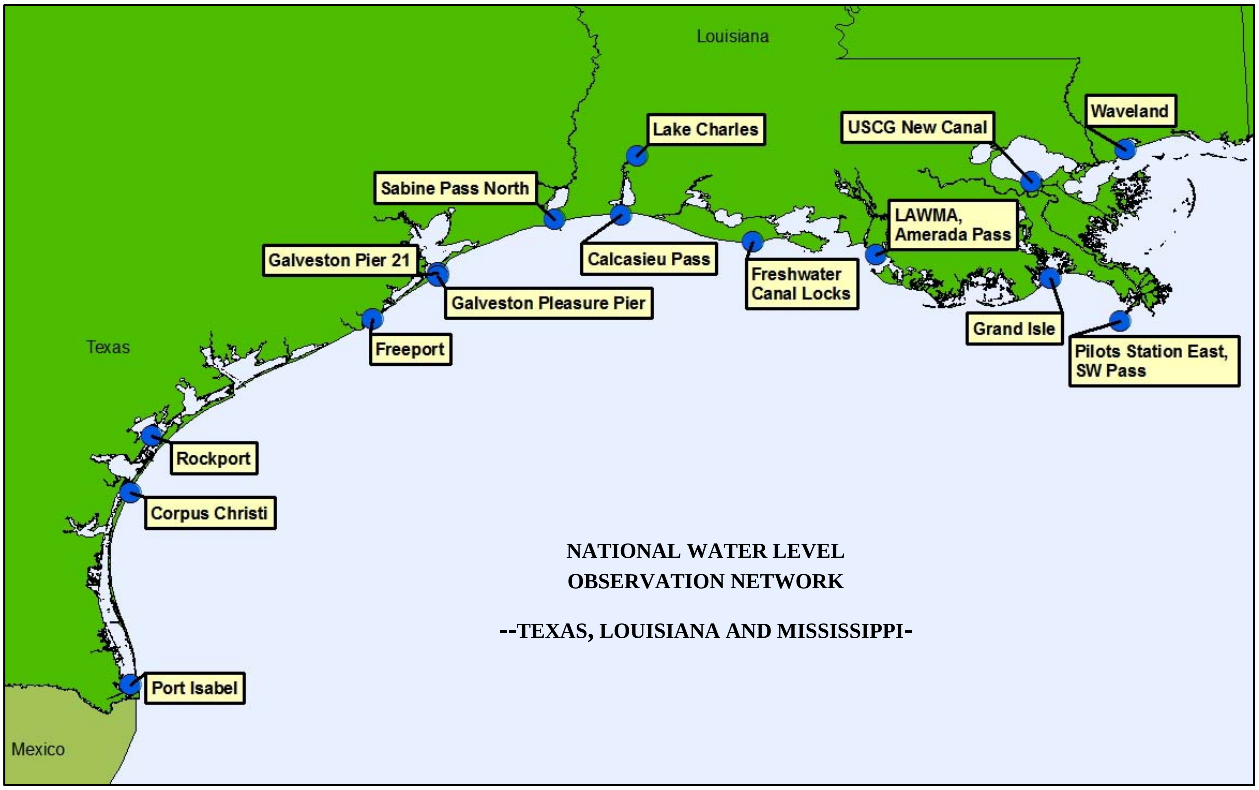
## **APPENDIX 1. National Water Level Observation Network (NWLON) Station Maps as of February 2008**

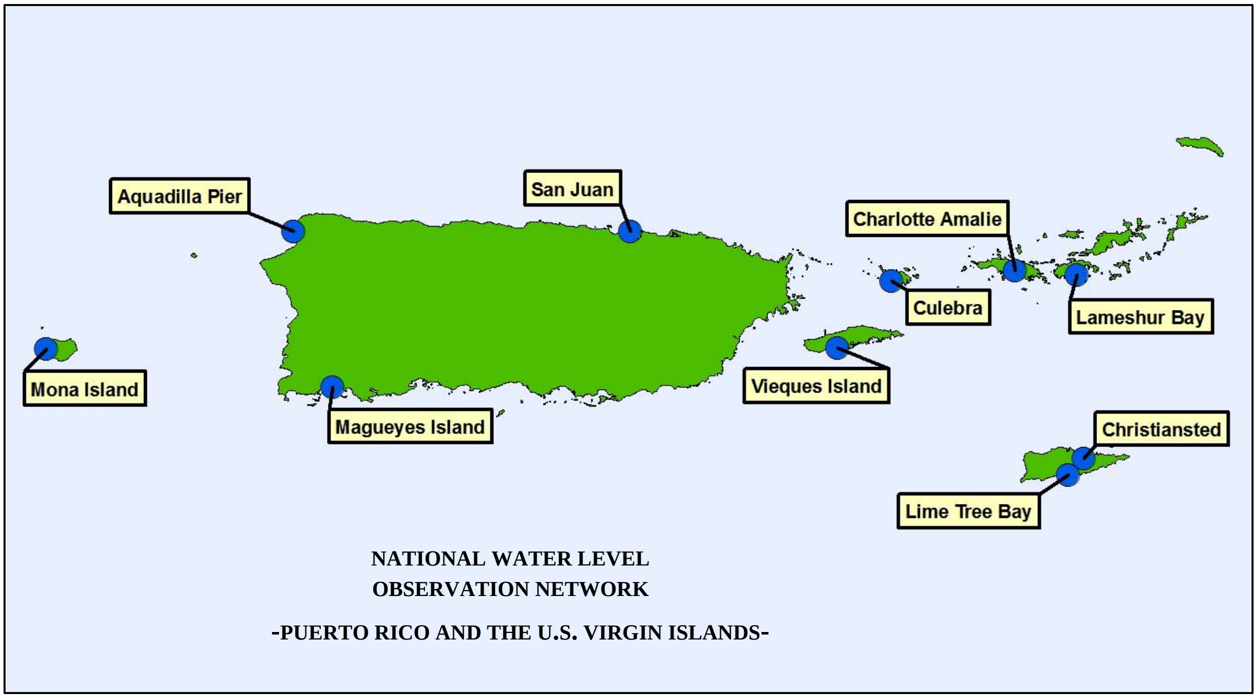


NATIONAL WATER LEVEL OBSERVATION NETWORK

-SOUTHERN NEW JERSEY TO GEORGIA-

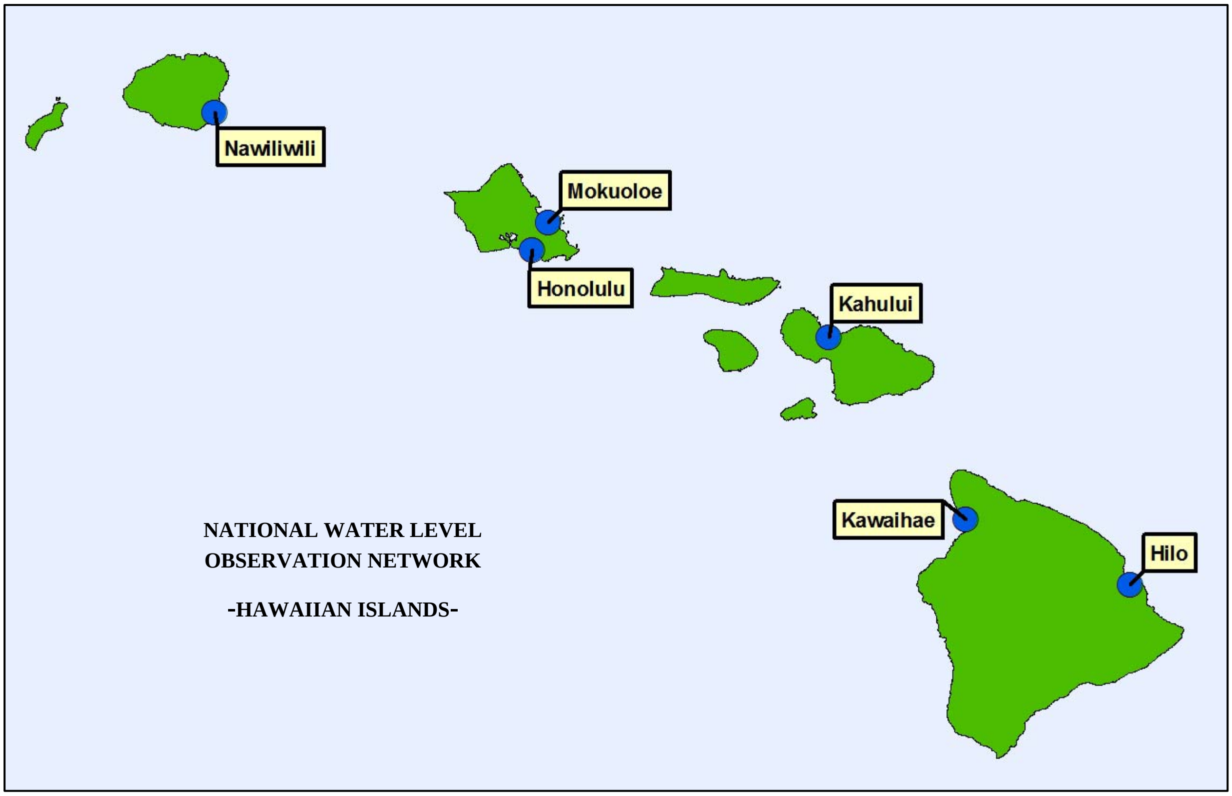

Alabama
Georgia
Florida
Mobile
Pensacola
Panama City Beach
Dauphin Island
Panama City
Apalachicola
Cedar Key
Fernandina Beach
Mayport (Bar Pilots Dock)
Trident Pier
Clearwater Beach
St. Petersburg
Fort Myers
Naples
Virginia Key
Key West
Key Colony Beach
Vaca Key
NATIONAL WATER LEVEL OBSERVATION NETWORK
-FLORIDA AND ALABAMA-


Louisiana
Texas
Mexico
Lake Charles
USCG New Canal
Waveland
Sabine Pass North
LAWMA, Amerada Pass
Galveston Pier 21
Calcasieu Pass
Freshwater Canal Locks
Galveston Pleasure Pier
Grand Isle
Pilots Station East, SW Pass
Freeport
Rockport
Corpus Christi
Port Isabel
NATIONAL WATER LEVEL OBSERVATION NETWORK
--TEXAS, LOUISIANA AND MISSISSIPPI-



NATIONAL WATER LEVEL
OBSERVATION NETWORK

-PUERTO RICO AND THE U.S. VIRGIN ISLANDS-

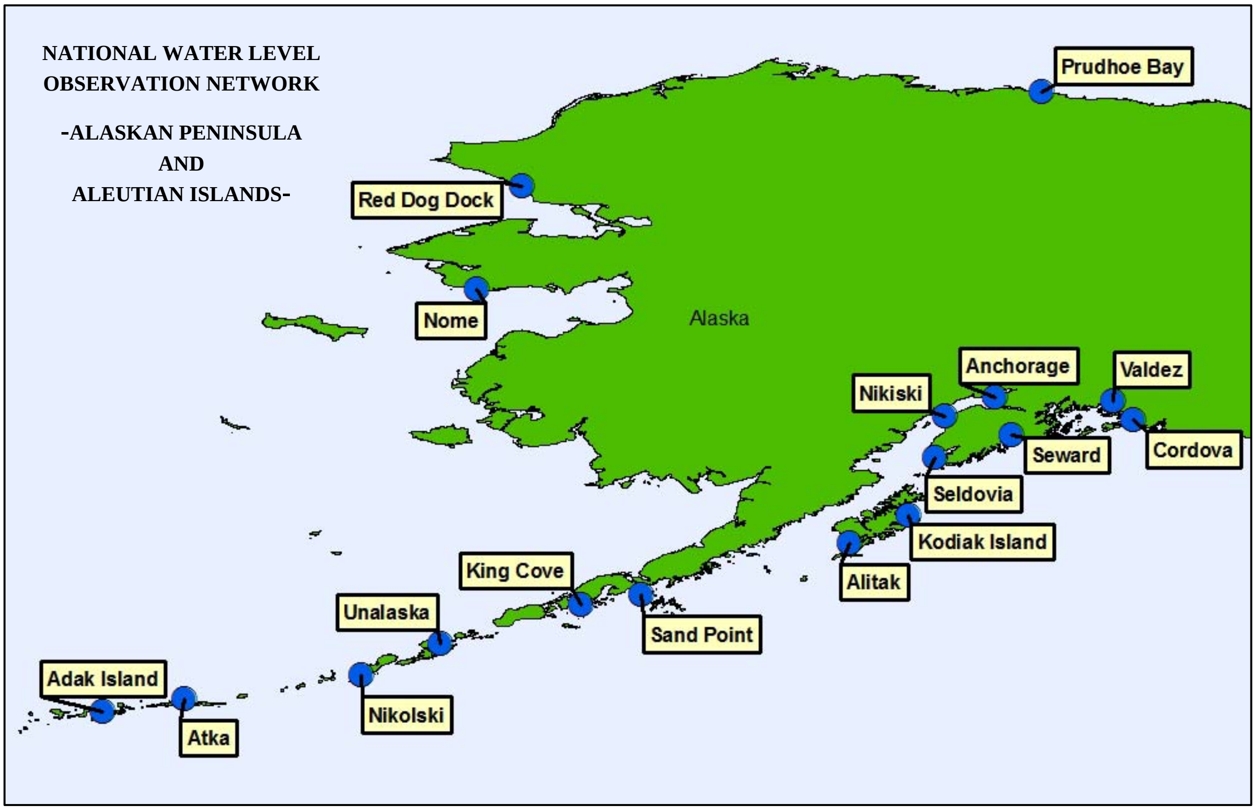


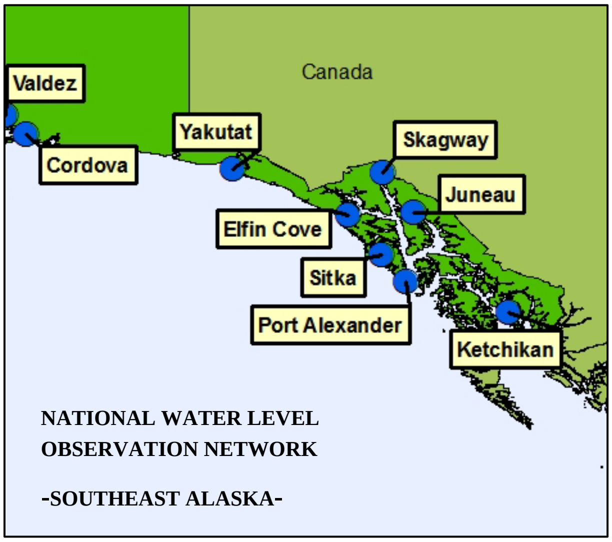
NATIONAL WATER LEVEL
OBSERVATION NETWORK

-HAWAIIAN ISLANDS-


Crescent City
North Spit
California
Arena Cove
Port Chicago
Point Reyes
Alameda
San Francisco
Monterey
Port San Luis
Santa Barbara
Santa Monica
Los Angeles
La Jolla
San Diego
Mexico
NATIONAL WATER LEVEL
OBSERVATION NETWORK
-CALIFORNIA-


NATIONAL WATER LEVEL OBSERVATION NETWORK
-WASHINGTON AND OREGON-
Canada
Cherry Point
Friday Harbor
Neah Bay
Port Townsend
La Push
Port Angeles
Seattle
Westport
Washington
Toke Point
Astoria
Garibaldi
South Beach
Oregon
Charleston
Port Orford


NATIONAL WATER LEVEL
OBSERVATION NETWORK
-ALASKAN PENINSULA
AND
ALEUTIAN ISLANDS-
Prudhoe Bay
Red Dog Dock
Nome
Alaska
Anchorage
Valdez
Nikiski
Seward
Cordova
Seldovia
Kodiak Island
Alitak
King Cove
Sand Point
Unalaska
Adak Island
Atka
Nikolski


Canada
Valdez
Cordova
Yakutat
Skagway
Juneau
Elfin Cove
Sitka
Port Alexander
Ketchikan
NATIONAL WATER LEVEL
OBSERVATION NETWORK
-SOUTHEAST ALASKA-

## APPENDIX 2. 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 construction is quite robust, and great care is taken in obtaining long-term continuous and valid water level data. 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. The tide houses used to house the equipment are designed to last 30-40 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). 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 A2-1 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 redundant set of DCPs and sensors are installed to reduce data loss. 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.

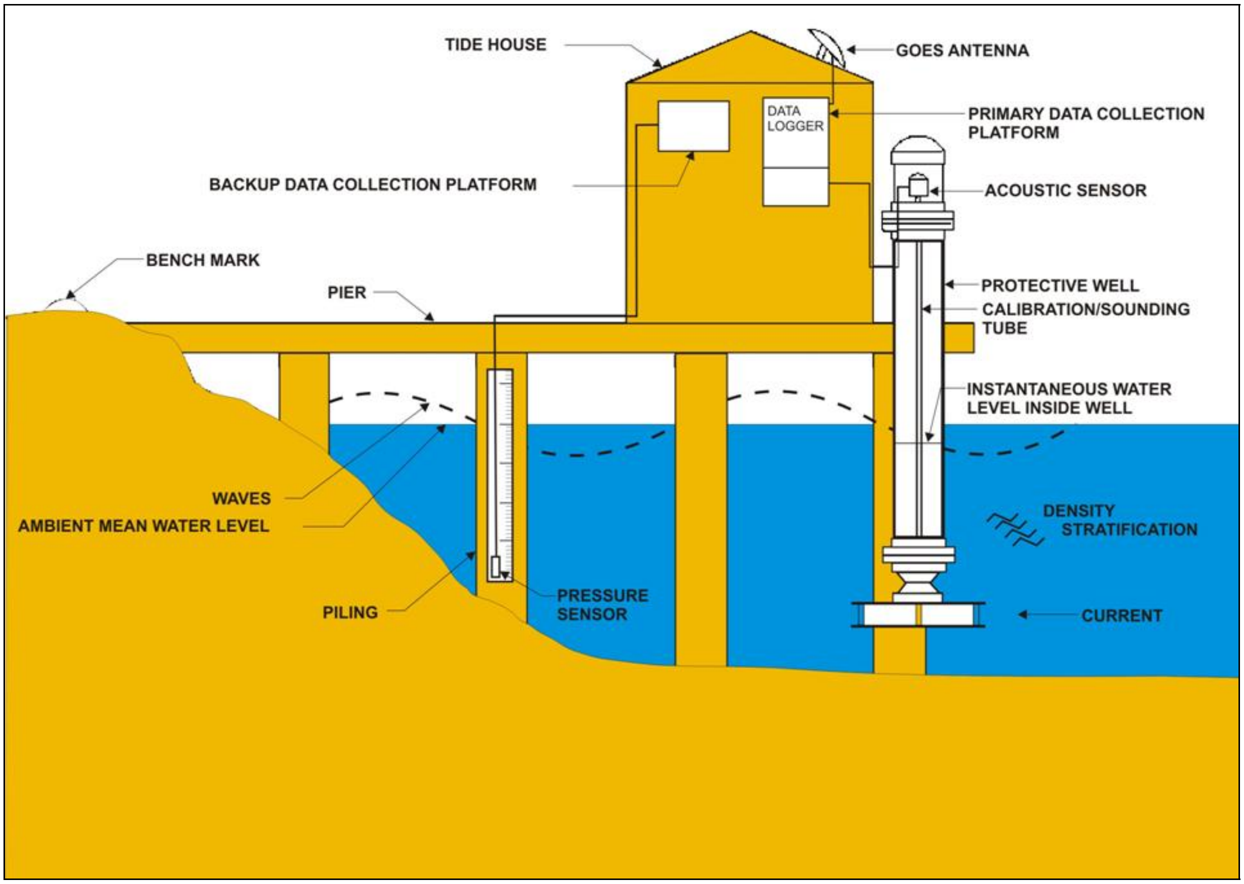


**Figure A2 -1.** One common NWLON station configuration including acoustic and pressure water level sensors with a primary and backup DCP. (NOAA, 2001)