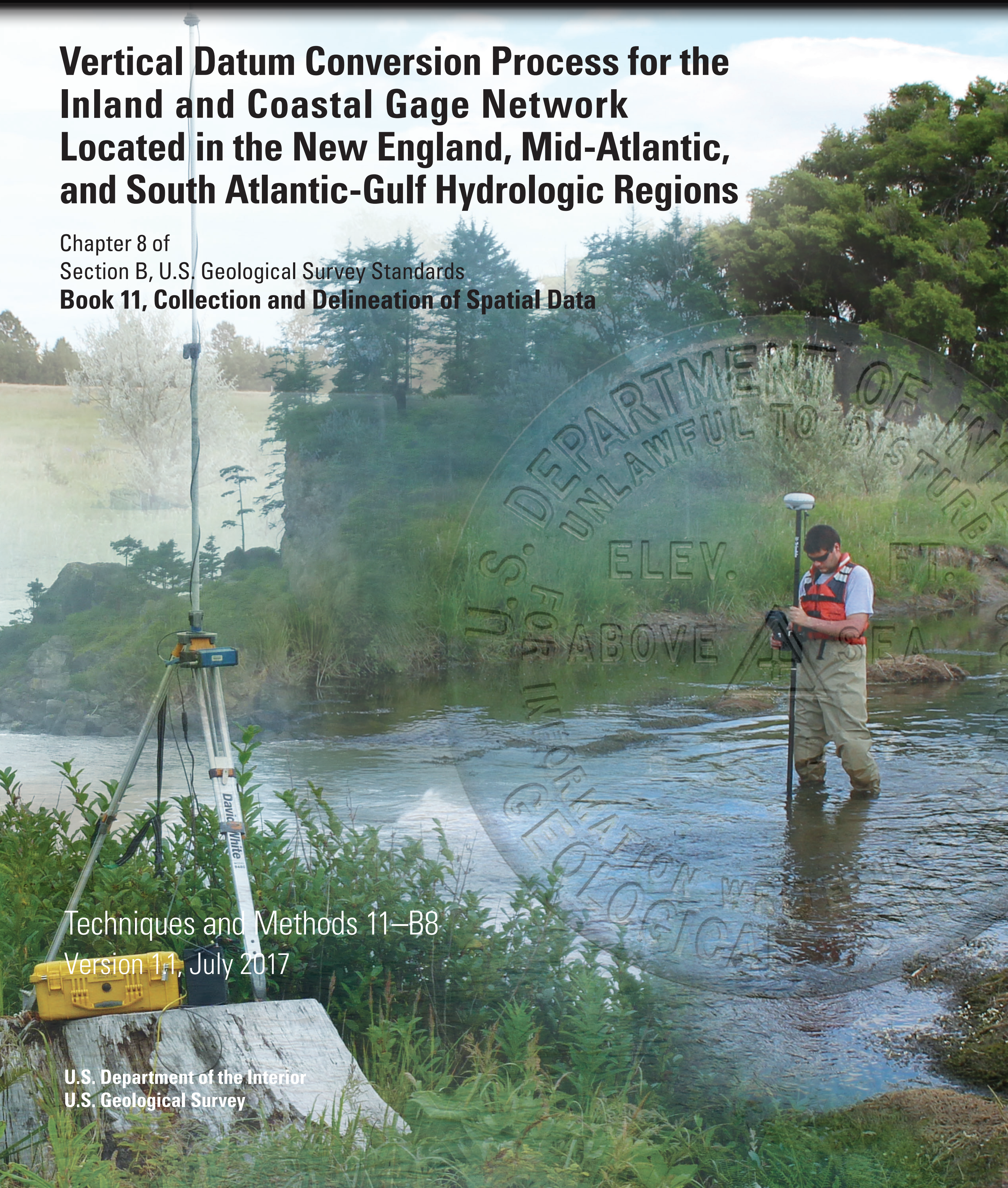
USGS
science for a changing world

Vertical Datum Conversion Process for the Inland and Coastal Gage Network Located in the New England, Mid-Atlantic, and South Atlantic-Gulf Hydrologic Regions

Chapter 8 of
Section B, U.S. Geological Survey Standards
Book 11, Collection and Delineation of Spatial Data



Techniques and Methods 11–B8
Version 1.1, July 2017

U.S. Department of the Interior
U.S. Geological Survey

Cover Photograph Credits

Quinault Indian Reservation, Washington State, 2012

The base station consists of Trimble R7 with a Zephyr Geodetic Model II antenna and RTK radio. The survey was performed on the Quinault Indian Reservation in 2012 in collaboration with the Washington State Department of Ecology and Oregon State University. Surveying of the beach elevations was done with GNSS backpacks and nearshore bathymetry with GNSS and single-beam echosounders mounted on personal watercraft. This was one of the benchmarks that was established to provide geodetic control for the survey.

Photograph by Andrew Stevens, USGS Oceanographer, Santa Cruz, California

Blue Creek near Lewellen, Nebraska, July 8, 2014

A USGS civil engineer surveys cross sections using survey-grade GNSS for a regional paleoflood study near USGS streamgage 06687000 Blue Creek near Lewellen, Nebraska, on July 8, 2014.

Photograph by Michael Stevens, USGS Hydrologist, Grand Junction, Colorado

Vertical Datum Conversion Process for the Inland and Coastal Gage Network Located in the New England, Mid-Atlantic, and South Atlantic-Gulf Hydrologic Regions

By Paul H. Rydlund, Jr., and Michael L. Noll

Techniques and Methods 11–B8
Version 1.1, July 2017

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
Jack Haugrud, Acting Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

U.S. Geological Survey, Reston, Virginia
First release: 2017
Revised: July 2017 (ver. 1.1)

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://store.usgs.gov/.

Suggested citation:
Rydlund, P.H, Jr., and Noll, M.L., 2017, Vertical datum conversion process for the inland and coastal gage network located in the New England, Mid-Atlantic, and South Atlantic-Gulf hydrologic regions (ver. 1.1, July 2017): U.S. Geological Survey Techniques and Methods, book 11, chap. B8, 29 p., https://doi.org/10.3133/tm11B8.

ISSN 2328-7055 (online)
ISSN 2328-7047 (print)

Preface

This series of manuals on techniques and methods describes approved scientific and data-collection procedures and standard methods for planning and executing studies and laboratory analyses. The material is grouped under major subject headings called “books” and further subdivided into sections and chapters. Section B of book 11 is about U.S. Geological Survey standards for data-collection techniques.

The unit of publication, the chapter, is limited to a narrow field of subject matter. These publications are subject to revision because of experience in use or advancement in knowledge, techniques, or equipment, and this format permits flexibility in revision and publication as the need arises.

Acknowledgments

The authors would like to thank Dru Smith, Daniel Martin, Scott Lokken, and Mark Schenewerk of the National Oceanic and Atmospheric Administration, National Geodetic Survey, for their technical reviews. Published manuals from the National Geodetic Survey, U.S. Army Corps of Engineers, National Weather Service, and the Federal Emergency Management Agency are referenced throughout the report.

Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to the distance above the vertical datum.

Altitude, as used in this report, refers to the distance above the vertical datum as referenced only to the Groundwater Site Inventory (GWSI) database as accepted GWSI nomenclature.

Abbreviations

AHPS	Advanced Hydrologic Prediction Service
CONUS	contiguous United States
CO-OPS	Center for Operational Oceanographic Products and Services
CORS	Continually Operating Reference Stations
CEPD	Comprehensive Evaluation of Project Datum
DNR	State Department of Natural Resources
DOD	United States Department of Defense
DOT	State Department of Transportation
DTL	Diurnal Tide Level
EDM	electronic distance measurements
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FGCS	Federal Geodetic Control Subcommittee
GNSS	Global Navigation Satellite System
GRACE	Gravity Recovery and Climate Experiment
GRAV-D	Gravity for the Redefinition of the American Vertical Datum
GWSI	Groundwater Site Inventory
HTML	HyperText Markup Language
IDB	Integrated Database
ITRF	International Terrestrial Reference Frame
MCU	Maximum Cumulative Error
MHHW	Mean Higher-High Water
MHW	Mean High Water
MLLW	Mean Lower-Low Water
MLW	Mean Low Water
MSL	Mean Sea Level
MTL	Mean Tide Level
NAVD 88	North American Vertical Datum of 1988
NFIP	National Flood Insurance Program
NGS	National Geodetic Survey
NGVD 29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration

NSRS	National Spatial Reference System
NWIS	National Water Information System
NWLON	National Water Level Observation Network
NWS	National Weather Service
OPUS	Online Position Users Service
OPUS-DB	Online Position Users Service - Database
OSW	Office of Surface Water
SLD 29	Sea Level Datum of 1929
SWaTH	Surge, Wave, and Tide Hydrodynamics Network
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VDATUM	Vertical Datum Transformation
VERTCON	North-American Vertical Datum Conversion
WSC	Water Science Center

Vertical Datum Conversion Process for the Inland and Coastal Gage Network Located in the New England, Mid-Atlantic, and South Atlantic-Gulf Hydrologic Regions

By Paul H. Rydlund, Jr., and Michael L. Noll

Abstract

Datum conversions from the National Geodetic Vertical Datum of 1929 to the North American Vertical Datum of 1988 among inland and coastal gages throughout the hydrologic regions of New England, the Mid-Atlantic, and the South Atlantic-Gulf have implications among river and storm surge forecasting, general commerce, and water-control operations. The process of data conversions may involve the application of a recovered National Geodetic Vertical Datum of 1929–North American Vertical Datum of 1988 offset, a simplistic datum transformation using VDatum or VERTCON software, or a survey, depending on a gaging network datum evaluation, anticipated uncertainties for data use among the cooperative water community, and methods used to derive the conversion. Datum transformations from National Geodetic Vertical Datum of 1929 to North American Vertical Datum of 1988 using VERTCON purport errors of ±0.13 foot at the 95 percent confidence level among modeled points, claiming more consistency along the east coast. Survey methods involving differential and trigonometric leveling, along with observations using Global Navigation Satellite System technology, afford a variety of approaches to establish or perpetuate a datum during a survey. Uncertainties among leveling approaches are generally <0.1 foot, and Global Navigation Satellite System approaches may be categorized with uncertainties of ≤0.1 foot for a Level I quality category and ≥0.1 foot for Level II or III quality categories (defined by the U.S. Geological Survey) by observation and review of experienced practice. The conversion process is initiated with an evaluation of the inland and coastal gage network datum, beginning with altitude datum components and the history of those components queried through the U.S. Geological Survey Groundwater Site Inventory database. Subsequent edits to the Groundwater Site Inventory database may be required and a consensus reached among the U.S. Geological Survey Water Science Centers to identify the outstanding workload categorized as in-office datum transformations or offset applications versus out-of-office survey efforts. Datum conversions or datum establishment for the inland or coastal gaging network should meet datum uncertainty requirements among other Federal agencies. Datum uncertainty requirements are ±0.25 foot for U.S. Army Corps of Engineers water-control or construction projects and ±0.16 foot for Federal Emergency Management Agency field surveys and checkpoint surveys used for mapping. River level forecasts generally are defined as ±0.10 foot among the National Oceanic and Atmospheric Administration–National Weather Service. Collaboration and communication among the cooperative water community is necessary during a datum conversion or datum change. Datum notification time-change requirements set by the National Oceanic and Atmospheric Administration–National Weather Service vary from 30 to 120 days, depending on datum conversion or datum-change case scenarios. Notification times associated with these case scenarios may be useful to the National Oceanic and Atmospheric Administration–National Weather Service and U.S. Army Corps of Engineers, because their daily operations are time sensitive, unlike the notification time change requirements of other entities that make up the cooperative water community. At the time of this writing, a future geopotential datum resulting from Gravity for the Redefinition of the American Vertical Datum is anticipated in 2022. A future version of VDatum and VERTCON is anticipated to provide a transformation among North American Vertical Datum of 1988 elevations to the new geopotential datum.

Introduction

Consistent and accurate elevation data are fundamental to water-data collection and water science by assuring effective management and protection of water resources, in addition to minimizing the loss of life and property as a result of water-related hazards. Examples such as flood protection and water capacity are concepts that require accurate elevation data to define the extent of protection or the availability of water. The U.S. Geological Survey (USGS) operates nearly 10,000 streamgages throughout the country that are used for a variety of applications, such as navigation, water control, power generation, transportation infrastructure, municipal public works, environmental compliance, flood forecasting, and recreation. Many of these applications depend on a vertical reference datum plane with minimized uncertainty and often require periodic evaluation.

The context of datum as referred to in this document reflects elevation as referenced to the National Spatial Reference System (NSRS), a system defined, managed, and maintained by the National Oceanic and Atmospheric Administration (NOAA), National Geodetic Survey (NGS), to ensure consistency among coordinate systems that define latitude, longitude, height, scale, gravity, and orientation throughout the United States (NOAA, 2016g). Datum as referred to in this document is more appropriately described as the geodetic datum or tidal datum, and a distinction should be made from a "gage zero" or local datum associated with a streamgage referenced to local benchmarks or reference marks that represent a surface used as a zero point for stage or gage height measurements. Geodetic datum essentially defines a land-based datum, which represents a set of constants specifying a coordinate system used for geodetic control, including all points and lines the coordinates, lengths, and directions of which have been determined by measurement and calculation (NOAA, 2016i). A tidal datum is referenced to a certain phase of the tide and is used to measure water levels with similar oceanographic characteristics (NOAA, 2016h).

The NSRS is a clearinghouse for datum revisions resulting from crustal motion, postglacial rebound, and subsidence. Two common geodetic datums—the National Geodetic Vertical Datum of 1929 (NGVD 29) and the North American Vertical Datum of 1988 (NAVD 88)—are referred to throughout the hydrologic regions of New England, the Mid-Atlantic, and the South Atlantic-Gulf, known as the tri-hydrologic region area. The Sea Level Datum of 1929 (SLD 29) was part of a general adjustment involving fixed locations at 26 tide gages—21 were in the United States and 5 were in Canada. SLD 29 was renamed NGVD 29 when it was officially adopted in 1976 (NOAA, 2016i). In 1991 an adjustment was made to NGVD 29, identifying NAVD 88 as a result of tectonic and local movement, coupled with monuments that had been destroyed (NOAA, 2016c). NAVD 88 was held fixed at only one tide gage (whereas 26 tide gages were referenced to NGVD 29) as a result of demonstrated variations in sea surface topography (NOAA, 2016i). The time span between the 1929 (SLD 29/NGVD 29) and 1991 (NAVD 88) adjustments encompassed the generation of a considerable amount of hydrologic data. The need to convert or update these data led to the 1993 directive issued from the Federal Geodetic Control Subcommittee (FGCS) to affirm NAVD 88 as the official civilian vertical datum for surveying and mapping performed or financed by the Federal Government (NOAA, 1993).

The conversion of geodetic datums at gaging stations does not involve one specific uniform, consistent, and transferrable approach for all gages in the tri-hydrologic region. An evaluation of the local gaging network datum and methodologies for conversion is required to ensure consistency and to further plan and evaluate costs associated with conversions.

Distinction and Purpose of Inland and Coastal Gages

The tri-hydrologic region consists of three nationally recognized hydrologic units—the New England, Mid-Atlantic, and South Atlantic-Gulf—that are delineated on the basis of natural drainage areas (Seaber and others, 1987). The tri-hydrologic region lies within 22 states along the eastern seaboard from Maine to Florida and along the Gulf Coast from Florida to Louisiana (fig. 1). Approximately 70 percent of the estimated 3,200 inland and coastal gages within the tri-hydrologic region reference a vertical datum other than NAVD 88, and about half of the gages reference NGVD 29 (USGS, 2016b).

The streamgaging network is cooperatively operated by the USGS and Federal, State, Tribal, and local agencies (Norris, 2010). The main purpose of the inland and coastal gage network is to provide water-quality and quantity information for the protection of life and property; provide information about flood, drought, and poor water-quality conditions; inform water-supply, sustainability, and regulatory decision making; guide infrastructure design, such as bridges, roads, and dams; and provide information for recreational activities. Data from coastal gages also are used to determine variability and long-term trends of sea level; determine water-quality conditions within marine environments; calibrate models that predict future sea level change; and provide critical information during intense coastal storms that can be used to protect life and property (NOAA, 2016e).

Geodetic datums (NGVD 29 or NAVD 88) typically are used as the origination datum for USGS coastal gage sites. Conversions from geodetic datums to tidal datums at coastal gage sites are used to better understand the tidal range at a site prior to installation of a gage.

The example of tidal datum heights above or below NAVD 88 shown in figure 2 is specific to the NOAA gage site located in Battery Park, New York County, New York.

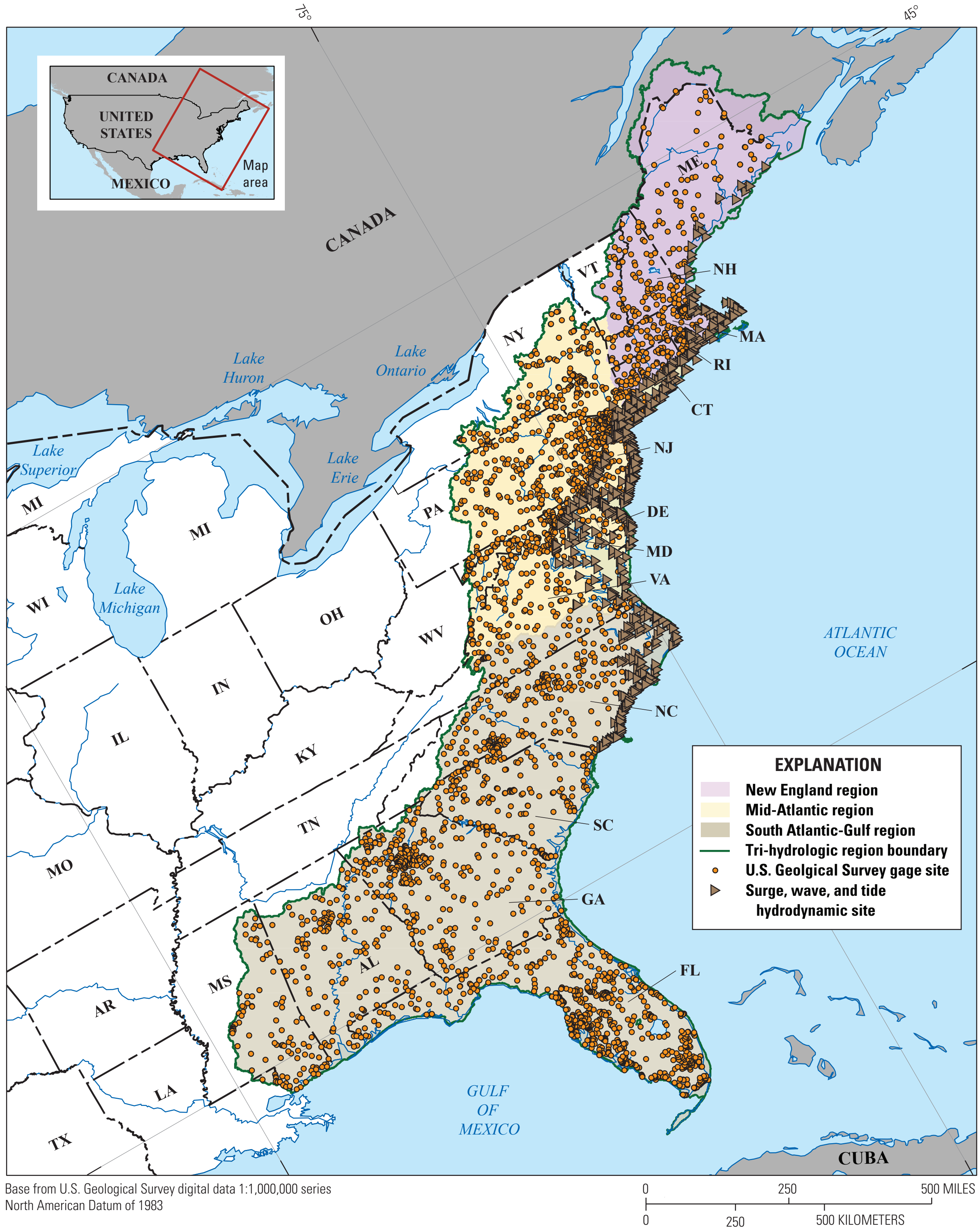
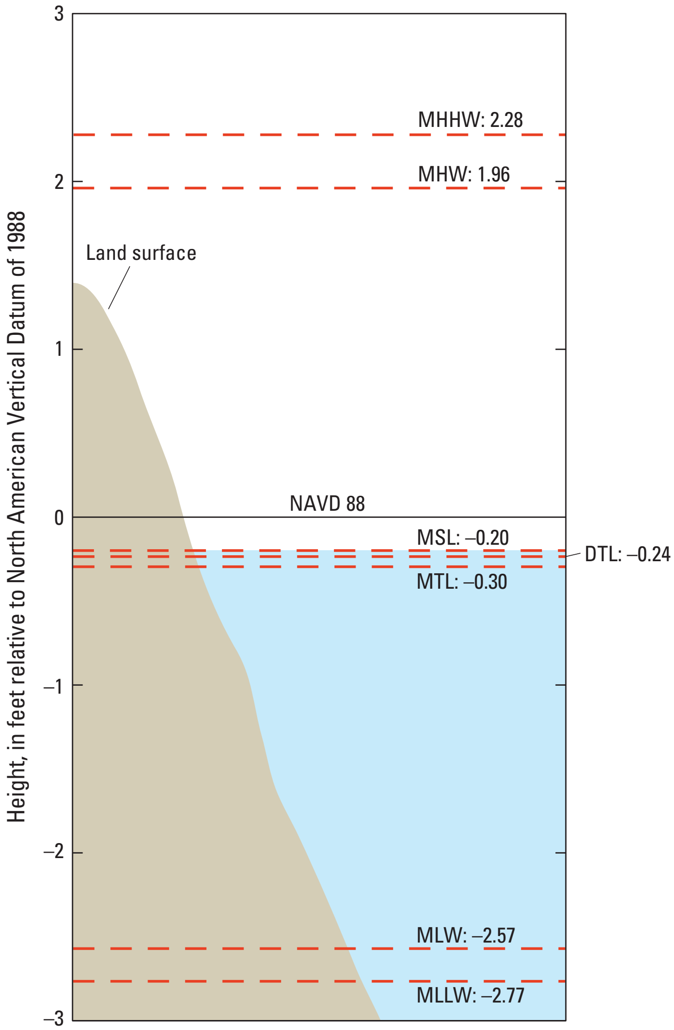


Figure 1. Tri-hydrologic region overview map illustrating the U.S. Geological Survey inland, coastal, and Surge, Wave, and Tide Hydrodynamics (SWaTH) gage networks.



EXPLANATION

MLW: –2.57	**Letters indicate tidal datum. Number indicates height above or below NAVD 88**
MHHW	**Mean higher-high water**
MHW	**Mean high water**
NAVD 88	**North American Vertical Datum of 1988**
MSL	**Mean sea level**
DTL	**Mean diurnal tide level**
MTL	**Mean tide level**
MLW	**Mean low water**
MLLW	**Mean lower-low water**

Figure 2. The relation of common tidal-based datum planes to the North American Vertical Datum of 1988 terrestrial-based datum plane at Battery Park, New York County, New York. Modified from National Oceanic Atmospheric Administration, 2016a.

The height of tidal datum above or below a geodetic datum is spatially variable and is dependent on the site-specific nature of oceanic characteristics at a particular gage site (NOAA, 2016h). Tidal datums should only be used as references to measure local water levels. The conversion values shown in figure 2 should not be applied to tidal datum conversions at other gage sites.

The New England, Mid-Atlantic, and South Atlantic-Gulf hydrologic regions are defined by the topography of a hydrologic area that contains either the drainage area of a major river or the combined drainage areas of a series of rivers (Seaber and others, 1987; fig. 1). The New England hydrologic region ultimately discharges water into the Bay of Fundy, the Atlantic Ocean between the States of Maine and Connecticut, the Long Island Sound (north of the New York and Connecticut State line), and Saint-Francois River, which is a tributary of the St. Lawrence River. This region comprises the States of Maine, New Hampshire, and Rhode Island, and parts of Connecticut, Massachusetts, New York, and Vermont. The boundary of the New England region extends beyond the United States border into Canada because the topography of the stream drainage basins was the primary feature used to determine hydrologic boundaries. The USGS National Water Information System (NWIS) indicates that approximately 420 inland and coastal gage sites are within the New England hydrologic region, also referred to as hydrologic region I (USGS, 2016b). Of the 420 gage sites, approximately 350 currently (2016) reference NGVD 29 or have an unreported datum, and 70 sites currently reference NAVD 88.

The Mid-Atlantic region, also referred to as hydrologic region II, comprises the States of Delaware and New Jersey, the District of Columbia, and parts of Connecticut, Maryland, Massachusetts, New York, Pennsylvania, Vermont, Virginia, and West Virginia (Seaber and others, 1987; fig. 1). Drainage from this hydrologic region discharges into the Atlantic Ocean between the States of New York and Virginia, the Long Island Sound south of the New York–Connecticut boundary, and the Richelieu River, which is a tributary of the St. Lawrence River. There are approximately 1,060 coastal and inland gage sites in region II, of which 670 sites reference a datum other than NAVD 88 (USGS, 2016b).

The South Atlantic-Gulf hydrologic region (region III) ultimately discharges drainage into the Atlantic Ocean between the States of Virginia and Florida, the Gulf of Mexico between the States of Florida and Louisiana, and the associated waters. Region III includes Florida and South Carolina, and parts of Alabama, Georgia, Louisiana, Mississippi, North Carolina, Tennessee, and Virginia (Seaber and others, 1987; fig. 1). The NWIS database indicates that approximately 1,270 of the 1,760 gage sites within the South Atlantic-Gulf region reference a datum other than NAVD 88 (USGS, 2016b).

Surge, Wave, and Tide Hydrodynamics (SWaTH) Network Gages

Following Hurricane Sandy in October 2012, the USGS developed a coastal monitoring network of long-term tide gages, rapid-deployment gages, and meteorological and storm-tide sensors that can be rapidly deployed and recovered during coastal storm events (Ron Busciolano, U.S. Geological Survey, written commun., 2016; fig. 1). The overland Surge, Wave, and Tide Hydrodynamics (SWaTH) network comprises approximately 750 sites within the tri-hydrologic region along the eastern seaboard in the States of Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, Pennsylvania, New Jersey, Delaware, Maryland, Virginia, and North Carolina and the District of Columbia (USGS, 2016c). Approximately 150, 450, and 150 of the 750 SWaTH network sites are within the New England, Mid-Atlantic, and South Atlantic-Gulf hydrologic regions, respectively. Data from the SWaTH network are disseminated in real time by way of the Internet to emergency responders and flood forecasters who track flood impacts, provide accurate warnings and advisories, assess flood damage, and rush appropriate assistance to flooded communities (USGS, 2016a).

Elevation data collected through the SWaTH network are currently reported in NGVD 29, NAVD 88, or a local vertical datum (McCallum and others, 2013; USGS, 2016c). Temporary short-term network sites such as rapid deployment gages and mobile storm-tide sensors reference NAVD 88 because objective points—an established point in a global navigation satellite system (GNSS) and considered to be a foresight in terrestrial surveying (Rydlund and Densmore, 2012)—typically are established with a GNSS survey and are configured to use the current vertical datum of the United States (NAVD 88; William Capurso, U.S. Geological Survey, written commun., 2016). Additionally, high water marks that are measured after large coastal storm events with conventional (terrestrial) or satellite-based surveying methods also reference NAVD 88. Some long-term USGS tidal and coastal gages that are part of the SWaTH network and reference NGVD 29 (or other datums) will need to be converted to NAVD 88 before storm-related data are disseminated (Ron Busciolano, U.S. Geological Survey, written commun., 2016). Less than 25 percent of the sites that compose the SWaTH network are considered long-term USGS coastal or tidal gages.

Datum Transformation Models

Datum transformations are executed by way of mathematical-based models. Vertical datum transformation models are developed using raw survey data, offering expediency in conducting a conversion from NGVD 29 to NAVD 88.

Vertical Datum Transformation (VDATUM)—Coastal Land-Water Interface

Historically NOAA and the USGS coordinated datum transformation efforts that tied coastal bathymetry to topographic digital elevation models, resulting in the development of the VDatum software. This software provides a suite of datum transformations with the intention of addressing vertical movement of coastal water levels and land in both space and time (NOAA, 2016i). VDatum transformations interrelate tidal datums among a land-based fixed benchmark representing a geodetic datum, typically NAVD 88.

Common tidal datums (table 1) are defined by a specific tide phase referenced to a 19-year period or epoch of time (National Tidal Datum Epoch 1983–2001) and are used as references to measure local water levels (Gill and Schultz, 2001). The tidal datum mean lower-low water (MLLW) is the most commonly used reference for predictions, benchmark publication, and nautical charting (Gill and Schultz, 2001). Coastal navigation projects and general surveying are commonly referenced to MLLW. Regarding the inland and coastal gage network, the primary use of VDatum is to convert tidal predictions from a MLLW datum to a geodetic datum that enables the residual water level (observation minus prediction) to be computed. If the residual water level is positive, it is generally considered to be storm surge (Christopher Schubert, U.S. Geological Survey, written commun., 2016).

There are 23 tidal regions or modeled grids within the tri-hydrologic region that are delineated by different oceanic characteristics. Tidal datum is specific to each modeled grid, requiring geodetic datum to relate tidal datums between grids.

Table 1. Common tidal datum representations from coastal gages.

[MSL, mean sea level; NTDE, national tidal datum epoch; MHW, mean high water; MLW, mean low water; MHHW, mean higher-high water; MLLW, mean lower-low water; MTL, mean tide level; DTL, diurnal tide level]

Tidal datum abbreviation	Definition
MSL	Arithmetic mean of hourly heights observed over the NTDE
MHW	Average of all high water observed over the NTDE
MLW	Average of all the low water heights observed over the NTDE
MHHW	Average of the higher-high water height of each tidal day observed over the NTDE
MLLW	Average of the lower-low water height of each tidal day observed over the NTDE
MTL	Arithmetic mean of mean high water and mean low water
DTL	Midway between mean higher-high water and mean lower-low water

Each of these modeled grids is developed by local tidal gage datum and represents expressions of random uncertainty quantified in terms of a standard deviation. Normally distributed, the standard deviation is a measurement of the average size of the error in the dataset (NOAA, 2016i). Error expressed by the use of VDatum is defined both by the source data and the process of the transformation. Datum transformations begin with International Terrestrial Reference Frame (ITRF), defined as a world spatial reference system defined by a geocentric system of coordinates, and continue through a series of core datums to output several classifications of vertical datum, both tidal and geodetic (NOAA, 2016i).

Some USGS offices use VDatum conversions at potential tide gage locations to understand the tidal range prior to platform installation. Offices such as Coram, N.Y., use VDatum to convert tidal predictions from MLLW to geodetic datum so water levels, more specifically storm surge, can be calculated at many gage sites located on Long Island, in New York City, and in downstate New York. For coastal flooding and storm surge, the National Weather Service (NWS) provides forecasts referenced to tidal datums such as MLLW and mean higher-high water (MHHW), which require VDatum conversions to relate the land-water interface.

The maximum cumulative error (MCU) is a representation of both source data and error in the transformation, which is obtained by the square root of the sum of the squares of the individual uncertainties from a sequence of conversions (NOAA, 2016i). The MCU is represented as a standard deviation (σ) at the 68 percent confidence level. Figure 3 illustrates an overview of these tidal regions and anticipated MCU for conducting datum transformations using VDatum, thereby giving the user an overall sense of error budget in the utility.

Tidal region uncertainties are a function of tidal range and tide-phase differences, bathymetric and coastal features, and the density and proximity of nearby geodetic and tide stations used in the assessment (NOAA, 2016i). For the 23 tidal regions within the tri-hydrologic region, MCU ranges from 0.26 foot (ft) to 0.56 ft. Maximum cumulative errors range from 0.31 ft to 0.56 ft for the New England region, 0.29 ft to 0.40 ft for the Mid-Atlantic region, and 0.26 ft to 0.56 ft for the South Atlantic-Gulf region.

North American Vertical Datum Conversion (VERTCON)

A common datum transformation utility known as VERTCON was initially developed in 1994 to provide a height conversion between common geodetic datums NGVD 29 and NAVD 88. The methodology involved the development of a physical model that was corrected to 381,833 datum difference (benchmark) values with a 68 percent confident predictive capability assessed at the ±0.065 ft uncertainty level (Milbert, 1999). Although confidence is generally more consistent in assuring ±0.065 ft uncertainties in the Eastern United States, it is ultimately best assured near modeled points or where two sets of leveling (NGVD 29 and NAVD 88) overlap (Milbert, 1999). One-fourth as many benchmarks are used for the NGVD 29 adjustment as are used for the NAVD 88 adjustment (Zilkoski and others, 1992), resulting in sparse regions where NGVD 29 data do not exist, thereby producing VERTCON uncertainties closer to the decimeter level or less in some areas (M. Armstrong, National Geodetic Survey, oral commun., 2014). For the tri-hydrologic region, NGVD 29 datum is approximately 0 to 1.3 ft above NAVD 88, with the exception of southern Florida where NGVD 29 is 1.3 to 1.6 ft above the NAVD 88 datum plane (Milbert, 1999).

The VERTCON model is developed from both NGVD 29 and NAVD 88 differential leveling lines. There are some cases where NGVD 29 “problem” lines may occur, often revealed when dramatic datum transformation differences are computed within a small area. For these circumstances, it may be appropriate to use a location slightly distant from the objective point to compute the transformation, no matter how close objective points may approach a recovered “problem” line revealed in the transformation (Milbert, 1999). The datum transformation utility will never achieve the uncertainty of geodetic leveling and is only reliable within the boundaries of the lower 48 United States (Milbert, 1999). For the tri-hydrologic region, the density of level lines for both NGVD 29 and NAVD 88 is generally more sufficient than in other parts of the country (D. Martin, National Geodetic Survey, oral commun., 2016). As a result of better representation of NGVD 29 and NAVD 88 level lines throughout most of the tri-hydrologic region, it may be generally assumed to use VERTCON with more consistency among a purported error of ±0.065 ft at the 68 percent confidence level and ±0.13 ft at the 95 percent confidence level. Assuming a general consistency of this error throughout the tri-hydrologic region, a conversion of an elevation with an inherent uncertainty or error greater than the purported error of the VERTCON utility is futile and should not be undertaken for the sake of conversion.

At the time of this writing, the NGS continues work to establish an error map associated with VERTCON transformations that are planned to be available through a newer version of VERTCON, tentatively referred to as VERTCON 3.0 (D. Smith, National Geodetic Survey, written commun., 2016).

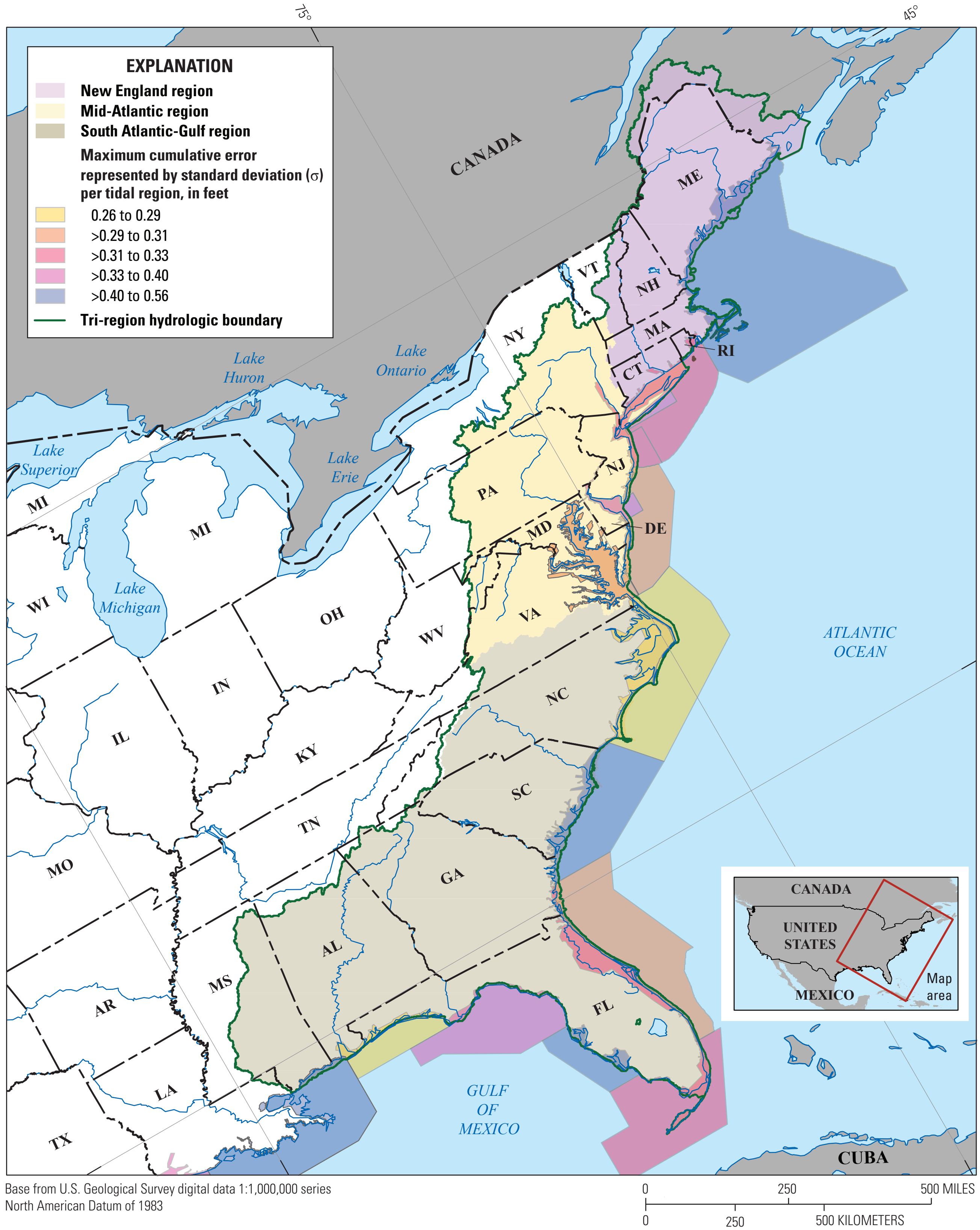


Figure 3. The maximum cumulative error represented by tidal region for datum transformations using the coastal land-water interface vertical datum transformation tool VDatum.

Datum Uncertainty Evaluation and Determination

Evaluation of vertical datum uncertainty should begin with the methodology used to perpetuate or establish vertical datum. Differential and trigonometric leveling, as well as GNSS-derived surveys, are common methods used to derive vertical datum, requiring an understanding of appropriate use and error analysis.

Differential Leveling Methods

Differential leveling (historically known as spirit leveling) conducted by the USGS began in the late 1800s for the purpose of establishing topographic control that predominantly followed third-order standards (Staack, 1938). Third-order standards set by the Federal Geodetic Control Subcommittee (FGCS) are generally desired to provide elevations for immediate control of cadastral, topographic, and construction surveys along with engineering projects (FGCS, 1984); however, more modern leveling conducted by the USGS, specifically at gaging stations, adopts first- and second-order requirements as well as third-order standards (Kenney, 2010). For local leveling circuits conducted at a gaging station, the absolute value of the closure error must be less than or equal to 0.003 ft $\sqrt{n}$, where n is the total number of instrument setups and may not exceed |0.015| ft regardless of the number of instrument setups (Kenney, 2010). Longer level circuits are typically required to perpetuate datum elevation from benchmarks to gaging stations. As a result, Kennedy (1990) acknowledges the third-order standard held early on for setting topographic control (Staack, 1938) and subsequently used to perpetuate datum elevation to leveling networks at gaging stations where closure error must be less than or equal to 0.05 ft $\sqrt{M}$, where M is measured in miles out and back in a level circuit. A rough terrain or hilly country allowance was subsequently noted by Kennedy (1990) where closure error must be less than or equal to 0.10 ft $\sqrt{M}$. A deviation from the third-order standard is noted by Kennedy, using ordinary equipment and procedures with longer site distances and rod readings to 0.01 ft, thereby acknowledging leveling errors that may exceed third-order standards (Kennedy, 1990). Allowable closure error defined by instrument setups may not exceed |0.015| ft (Kenney, 2010), which may imply a limited allowable circuit length opposed to allowable closure error defined by unlimited distance (Kennedy, 1990). In general, differential leveling continues to be the most accurate method for perpetuating elevation, affording measurement precision to 0.001 ft for closure errors defined by instrument setups and 0.01 ft for those errors defined by distance.

Trigonometric Leveling Methods

Total station instruments essentially are electronic theodolites combined with an electronic distance measurement (EDM) device used to obtain horizontal, vertical, and slope distances that translate to X-Y-Z coordinates through an onboard microprocessor (U.S. Army Corps of Engineers [USACE], 2007). Total station instruments can be categorized by the angular uncertainty of the instrument, expressed as arc-seconds. In theory, elevation error resulting from angular uncertainty can be calculated by taking the cosine function of 90º plus or minus the angular uncertainty of the total station multiplied by the foresight distance. For example, a 5 arc-second total station that measures an objective point 500 ft from the instrument can expect an error of ±0.012 ft (Kavanagh, 2004). Angular uncertainties less than 5 arc-seconds generally are referred to as more precise, whereas those above 5 arc-seconds are referred to as construction grade. The total station instrument is not limited to a horizontal line of sight and is commonly used to measure elevation differences determined from observed vertical angles and known distances, a process defined as trigonometric leveling.

Although a variety of trigonometric leveling procedures using total station instruments have been defined in several sources of literature, common assurances involve averaging multiple observations of reciprocal direct and reverse zenith angle measurements (also known as face 1 and face 2 measurements) within a limited site distance, generally not to exceed 500 ft. Adhering to rigorous field procedures and accounting for error sources stemming from the environment, instrument, and operation, some literature sources proclaim third-order standards with maximum site distances of as much as 1,000 ft (USACE, 2007). Field procedures involve care in instrument setup and leveling, sun and wind protection, quality prism reflectors and offsets, accurate accounting of pressure and temperature, accounting of curvature and refraction, visible and accurate target pointing, routine collimation or calibration, plumb assurance, limited site distances, and multiple observations of reciprocal measurements. Additionally, differential leveling results can be compared to trigonometric leveling results using the same control points (and same atmospheric conditions) to evaluate the accuracy of the trigonometric leveling method (Kavanagh, 2004). As a rule of thumb, total station instruments require annual manufacturer service calibrations that address such things as EDM alignment and offsets as part of testing to assure product specifications for angular uncertainty and distance.

Combining vertical angle and distance error sources related to the environment, instrument, and operation over a 500-ft line generally yields ranges from –0.02 to +0.05 ft in vertical angle measurements and –0.04 to +0.05 ft in distance measurements (USACE, 2007). Although both angular and distance-related errors are inherent to the total station, owing to the angular uncertainty of the instrument, the dominant error source is generally attributed to distance. As a result, trigonometric leveling should employ circuits with closing error revealed on the origin mark that is proportioned along the line (between objective points) by distance. Method comparisons from cited sources and general practice assure trigonometric leveling can maintain uncertainties of <0.1 ft (USACE, 2007; Grgić and others, 2010; Nestorović and Delčev, 2014).

Although the precision of this method is generally subordinate to differential leveling, an increase in efficiency through hilly terrain generally outweighs an increase in allowable error. For distances (between instrument setups) ≤500 ft, using instruments with angular accuracy <5 arc-seconds that abide by strict field procedures and accounting for error sources noted prior, trigonometric leveling is the second-most precise method of perpetuating datum elevation to leveling networks at gaging stations to 0.01 ft.

Global Navigation Satellite System (GNSS) Methods

The most common method of establishing geodetic datum at gaging stations involves the use of GNSS observations. Overall error assessments are difficult to quantify because measurements are based on the uncertainty of the hybrid geoid model and instrument specifications as well as error sources recovered in the field that pertain to sufficient observations, position dilution of precision, receiver communication, multipath signals, and proper identification of the antenna and reference point (Rydlund and Densmore, 2012). Although distance-weighted error and fixed error in real-time GNSS equipment are more definitive—generally 0.065 ft (fixed) + 1 part per million (distance)—the error is only a fraction of the overall error budget.

Quality representations of GNSS surveys are categorized by Rydlund and Densmore (2012) as a result of the difficulty of numerically representing uncertainty in the method. An assessment of the quality of the fiducial benchmark (attributes lending to confidence as a basis for comparison) used for observations is taken into consideration along with effective field practice, such as bubble check and calibration of tripods or bipods, stabilization of tripods or bipods, sufficient mission planning, and assurance of the antenna reference point (Rydlund and Densmore, 2012). Quality categories of GNSS survey Levels I, II, and III are all identified as a survey-grade or centimeter-level precision (0.033 ft) approach. As a result of years of method practice referenced to Rydlund and Densmore (2012) and surveying efforts along the Atlantic Gulf Coast during Hurricane Sandy (McCallum and others, 2013), a general distinction has been made between Level I surveys that generate an approximate uncertainty of ≤0.1 ft and Level II and III surveys that generate an approximate uncertainty of ≥0.1 ft. This is a general distinction and may not be consistent because uncertainty approximates may interchange among quality categories. For example, a single-base Online Positioning User's Service (OPUS) post-processed survey that meets all of the Level I criteria may have a vertical peak-to-peak orthometric value (representative uncertainty value, Rydlund and Densmore, 2012) of 0.23 ft, which exceeds the ≤0.1 ft categorization for a Level I survey. Although establishing or perpetuating datum elevation using GNSS methods may be more efficient and cost effective, the method continues to generate more uncertainty on average than differential and trigonometric leveling.

A generalization of method precision and uncertainty is provided in table 2. Method uncertainties are useful for evaluating the datum conversion process as well as meeting datum uncertainty requirements among the cooperative water community.

Table 2. Summary of survey methods with precision estimates and expected uncertainties.

[ft, foot; √, square root; *n*, number of station setups; *M*, measured distance in miles out and back; <, less than; ≤, less than or equal to; ≥, greater than or equal to; GNSS, Global Navigation Satellite System]

Survey method	Precision (ft)	Uncertainty (ft)
Differential leveling by station setups	0.001	[1]$0.003\sqrt{n}$
Differential leveling by distance	0.01	$0.05\sqrt{M}$ or [2]$0.10\sqrt{M}$
Trigonometric leveling	0.01	<0.1
GNSS Level I	0.03	[3]≤0.1
GNSS Level II and III	0.03	[3]≥0.1

[1]Not to exceed |0.015| regardless of instrument setups.

[2]Rough terrain or hilly country allowance.

[3]Approximates from general practice.

Datum Conversion Process

Throughout the tri-hydrologic region, the cooperative streamgage network continues to be predominantly represented by NGVD 29, NAVD 88, datums loosely derived from topographic or digital elevation products, and datums that are simply unreported. Despite the 1993 directive issued from the FGCS to affirm NAVD 88 as the official civilian vertical datum, nearly two-thirds of the streamgage network is represented by NGVD 29 or a derivation from topographic or digital elevation products. A requisite survey or resurvey may be cost prohibitive, requiring a further evaluation of the network and conversion techniques to offer low-cost alternatives.

Evaluation

An evaluation of the gaging network and information sources used to provide datum elevation must be conducted as a first step in the datum conversion process. Data mining through the USGS Groundwater Site Inventory (GWSI) System database should begin with querying datum components as suggested in table 3 (USGS, 2004). Subsequent datum codes for altitude determination (table 4), geodetic vertical datum of altitude determination (table 5), and reason for datum change (table 6) are useful querying subset information in supplementing the initial evaluation of the network (USGS, 2004). The GWSI database may uncover unreported datum and there may be occurrences when datum codes may not be appropriately reflected in GWSI and should be scrutinized after the initial evaluation. Suspect codes should

Table 3. Suggested altitude datum history querying of the U.S. Geological Survey Groundwater Site Inventory (GWSI) database to evaluate gaging networks for datum conversion.

Subsection	Attribute name	Description	Definition
9.3	alt_datum_hist_tp	Altitude type (C740) MANDATORY	Provides a distinction between a gage datum (surface-water stations) and a land-surface datum (groundwater wells)
9.5	alt_datum_hist_va	Altitude of datum (C277) MANDATORY	Altitude of the gage height of zero flow or floor of the gage house (surface-water stations) geodetic datum of the land-surface reference mark (groundwater wells)
9.6	alt_datum_hist_acy_va	Altitude accuracy (C279) CONDITIONALLY MANDATORY	Accuracy of altitude expressed in terms of possible error
9.7	alt_datum_hist_meth_cd	Method altitude determined (C280) MANDATORY	Method code for altitude determination (see table 4)
9.8	alt_datum_cd	Geodetic vertical datum of altitude (C278) MANDATORY	Method code for geodetic vertical datum of altitude determination (see table 5)
9.11	alt_datum_hist_rsn_cd	Altitude reason code, indicating the reason this altitude record was established (C283) MANDATORY	Reason codes for changes in the altitude of a datum (see table 6)
9.13	alt_datum_hist_tx	Altitude datum remark, must include a description of the location of the gage datum or land-surface datum (C286)	Provides a description of the location of the atitude datum at land-surface datum or gage datum

Table 4. Availability of determined altitude method in the U.S. Geological Survey Groundwater Site Inventory (GWSI) database.

[DGPS, differential global positioning system; SGPS, survey grade global positioning system; DEM, digital elevation model; GNSS, Global Navigation Satellite System; IFSAR/ifsar, interferometric synthetic aperture radar; LIDAR/lidar, light detection and ranging; FY, fiscal year, which is the period from October 1 to September 30 and is identified by the year in which the period ends]

Method code	Method name	Method description
DGPS	DGPS	Differential global positioning system—NOT FOR NEW DATA ENTRY if GNSS methods used. Historically used and includes DGPS and SGPS methods. After October 2014 only use if commercial DGPS of submeter accuracy was used or for international data.
SGPS	SGPS	Survey grade global positioning system—NOT FOR NEW DATA ENTRY if GNSS methods used after October 2014 (FY 2015). May include survey grade GPS and GNSS methods prior to October 2014. After October 2014 only use if commercial DGPS of submeter accuracy was used or for international data.
LEVEL	Leveling	Leveling or other surveying method
MAP	Topo Map	Interpolated from topographic map
DEM	Digital Elevation Model	Interpolated from digital elevation model based on topographic map
IFSAR	ifsar	Interpolated from digital elevation model based on interferometric synthetic aperture radar, airplane (ifsar)
LIDAR	lidar	Interpolated from digital elevation model based on light detection and ranging, airplane (lidar)
REPRT	Reported	Reported
UNKWN	Unknown	Unknown (used for transfer only)
GPS	Global Positioning System	Use for transfer only—NOT FOR NEW DATA ENTRY. Historically used and includes DGPS and SGPS. NOTE mapping grade GPS should only be used for latitude and longitude and then use other method for altitude, such as interpolate from topographic map or DEM.
GNSS1	GNSS-Quality Level 1	Level 1 Quality Survey Grade Global Navigation Satellite System[1]
GNSS2	GNSS-Quality Level 2	Level 2 Quality Survey Grade Global Navigation Satellite System[1]
GNSS3	GNSS-Quality Level 3	Level 3 Quality Survey Grade Global Navigation Satellite System[1]
GNSS4	GNSS-Quality Level 4	Level 4 Quality Survey Grade Global Navigation Satellite System[1]

[1]Rydlund and Densmore, 2012.

first be modified to correctly represent all datum components at gaging locations. In addition, there may be datum updates that have not been uploaded into GWSI, such as locally stored metadata that should be investigated. After a final evaluation of quality assured and updated GWSI datum components, a summary list should prevail, indicating the extent of the gaging network requiring datum conversion.

In addition to current gage network datum evaluations, it is necessary to assess proximity of trusted benchmarks to gage locations. The trusted benchmark has the assurance of quality and stability, and represents a current datum and adjustment that is recommended for GNSS localizations (Rydlund and Densmore, 2012). The National Geodetic Survey Integrated Database (NGS-IDB) is the most appropriate source for recovering benchmark information and benchmark evaluation. Aside from extracting benchmark information from the NGS-IDB, applications such as DSWORLD (NOAA, 2016b) and Find-A-Control (Critigen, 2016) are common smart device utilities referenced to the NGS-IDB that are often used in the field. The mission of the NGS is to define, maintain, and provide access to the NSRS. Part of the NGS mission includes dissemination of survey benchmark information in the form of a datasheet (NOAA, 2015b). Datasheets extracted from the NGS-IDB report first- and second-order benchmarks with heights expressed to ±0.01ft and third-order benchmarks to ±0.1 ft. Although some GNSS approaches rely solely on active monumentation, based on continually operating reference stations (CORS) to establish gage datum, benchmarks should continue to be used as a frame of reference or localization for most GNSS methods (in addition to differential and trigonometric leveling methods) like static network, static single-base OPUS-S and RS, and real-time positioning surveys (Rydlund and Densmore, 2012).

Fiducial benchmarks are preferred to represent uncertainties of first- or second-order (±0.01 ft) benchmarks. In addition to leveling error in the third-order network, third-order benchmarks are established from first- and second-order leveling networks, resulting in cumulative leveling error reflected in the third-order mark (Ogundare, 2015). Although third-order benchmarks inherently have more uncertainty than first- or second-order marks, the magnitude of this uncertainty (Ogundare, 2015) is generally marginal compared to the uncertainty expressed in the various methods of perpetuating datum (table 2). In addition, third-order marks have historically represented (to a lesser degree) fiducial benchmarks for leveling at USGS gaging stations and establishing datum. At a minimum, the use of a trusted third-order (as well as first and second order) benchmark as a fiducial mark would

Table 5. Availability of geodetic vertical datum of altitude in the U.S. Geological Survey Groundwater Site Inventory (GWSI) database.

Code	Geodetic vertical datum of altitude
NGVD29	National Geodetic Vertical Datum of 1929
NAVD88	North American Vertical Datum of 1988
OLDAK	Old Alaska (Mainland) and Aleutian Island Datum
PRVD02	Puerto Rico Vertical Datum of 2002
LMSL	Local Mean Sea Level
GUVD04	Guam Vertical Datum of 2004
ASVD02	American Samoa Vertical Datum of 2002
NMVD03	Northern Marianas Vertical Datum of 2003
IGLD	International Great Lakes Datum
COE1912	U.S. Army Corps of Engineers datum adjustment 1912
BARGECANAL	New York State Barge Canal datum
OLDPR	Old Puerto Rico and Virgin Island Datum
HILOCAL	Local Hawaiian Datum
ASLOCAL	Local American Samoa Datum
GULOCAL	Local Guam Datum
TIDELOCAL	Local Tidal Datum

Table 6. Availability of altitude datum change reason codes in the U.S. Geological Survey Groundwater Site Inventory (GWSI) database.

[LSD, land-surface datum; GA, gage datum]

Code	Reason
ACRCY	Better measurement of LSD or GA (not a true change in altitude of the reference point)
CMPCT	LSD or GA change from compaction or opposite process: groundwater extraction, hydro compaction (wetting of collapsible soils); rebound, uplift
CNSTR	LSD or GA change from construction, destruction
CONVT	Conversion from a vertical datum (by mathematics or software)
DEPSN	LSD or GA change from deposition (landslides)
EROSN	LSD or GA change from erosion (landslides)
ERTHQ	LSD or GA change from earthquakes
GLACL	LSD or GA change from glacial rebound
INITL	Initial measurement of LSD or GA
OSOXI	LSD or GA change from organic soil oxidation or similar processes
PMFST	LSD or GA change from thawing or freezing permafrost
RELOC	LSD or GA change due to relocation of gage at a site
RSRVY	Re-surveyed to a geodetic vertical datum
TCTNC	LSD or GA change from tectonic (geologic) uplift or subsidence
UNKWN	Unknown reason for LSD or GA change
VOIDS	LSD or GA change from collapsible voids: mining, sinkholes, piping
VOLCN	LSD or GA change from volcanism

require publication in the NGS-IDB. In addition to geodetic information reviewed from the NGS-IDB datasheet, a Level I or Level II single-base static GNSS observation as described by Rydlund and Densmore (2012) may be conducted to further trust the use of any benchmark selected as fiduciary.

Process Selection and Execution

The process of conversion begins with an evaluation of the existing datum of the gaging network and surrounding benchmark quality and availability as described previously. The next step involves the conversion selection process beginning with the fiducial mark (fig. 4). If there is no evidence of a fiducial mark, a survey is required; however, evidence of a fiducial mark requires evidence of a survey tie to reference marks at the gaging location and further evaluation to ensure the fiducial mark is not subject to land-surface motion (subsidence or uplift).

The measured CORS velocities (NOAA, 2016a) offer a general sense of the vertical movement illustrated for the New England (fig. 5), Mid-Atlantic (fig. 6), and South Atlantic-Gulf (fig. 7) hydrologic regions; however, the broad trends depicted in figures 5, 6, and 7 must always be tempered with descriptions of stability for each mark or area (for example, descriptions from the NGS datasheets). Although many benchmarks have deep rod construction or corrosion resistant metal disks set in a bedrock outcrop that prohibits excessive movement (FGCS, 1984; M. Schenewerk, National Geodetic Survey, oral commun., 2016), a localized disturbance such as land subsidence is possible. For example, subsidence has been particularly notable since the 1940s in the southern Chesapeake Bay region at rates of 0.004 to 0.016 foot per year (Eggleston and Pope, 2013). In addition to sea-level rise, aquifer compaction from groundwater pumping in the southern Chesapeake Bay region has indicated movement as illustrated in figure 8 (Eggleston and Pope, 2013).

Marks not subject to subsidence and uplift should be evident in the NGS-IDB and investigated further to assure absence of anthropogenic disturbance, adequate stability, and frequent usage as indicated in station recovery notes. It is recommended that fiducial marks be published in the NGS-IDB; however, there may be instances where fiducial marks are derived from local leveling networks, not published in the NGS-IDB, and may be used as exceptions with the assurance that first- or second-order standards as defined by the FGCS are evident in the metadata. The use of a third-order mark as a fiduciary mark requires publication in the NGS-IDB to assure that first- or second-order criteria have been met. Leveling-derived marks or leveled heights are preferred fiducial marks, but GNSS-derived marks published in the NGS-IDB that are derived from a height modernization project are suitable for use because these are established by meticulous procedures as outlined by Zilkoski and others (2008).

Referring to figure 4, the outcome of the conversion process may be a survey, application of an offset between published NAVD 88 and NGVD 29 elevations, or the use of VDatum or VERTCON. As a result of extensive NGVD 29 and NAVD 88 leveling in the tri-hydrologic region, the use of VERTCON for datum conversions from recovered fiducial marks published in the NGS-IDB should have good consistency in representing a purported error of ±0.065 ft at the 68 percent confidence level and ±0.13 ft at the 95 percent confidence level. However, an assurance check may be conducted using the following steps:

1. Locate published benchmarks that represent a superseded NGVD 29 elevation and a NAVD 88 elevation in the NGS-IDB that are nearest to the fiducial mark.

2. Execute VERTCON on the fiducial mark and nearest benchmarks published in the NGS-IDB.

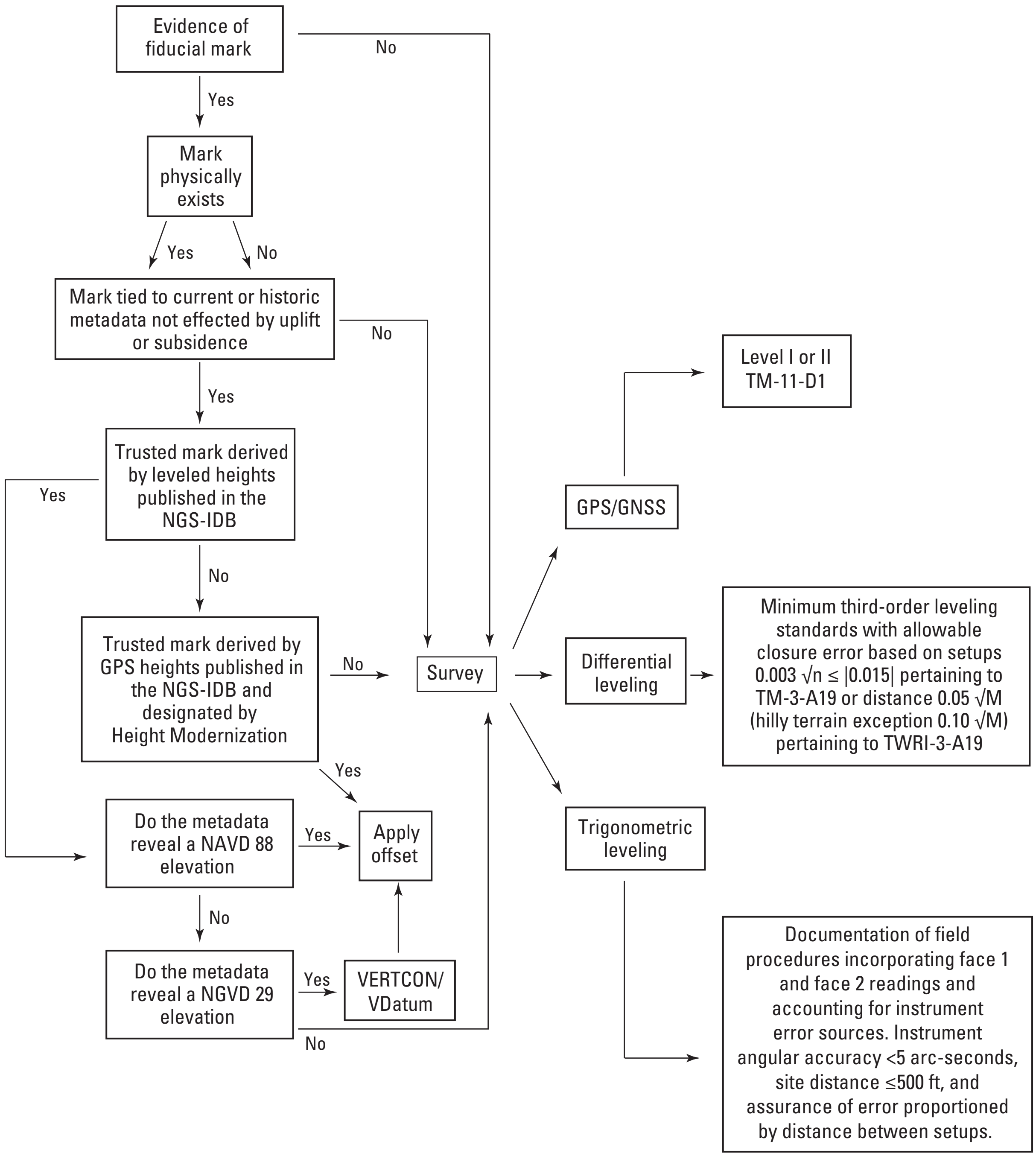
3. Compare the datum shift (difference) between published NGVD 29 and NAVD 88 elevations on the nearest benchmarks and the datum shift resulting from the VERTCON transformation on those same nearest benchmarks. Published NGVD 29 and NAVD 88 differences compared to the VERTCON results should generally have agreement within ±0.065 ft (68 percent confidence) and ±0.13 ft (95 percent confidence).

4. Compare the datum shift on the fiducial mark using VERTCON to the shift observed on the nearest surrounding benchmarks.

For smaller areas, datum shifts should be relatively consistent among the surrounding benchmarks and the fiducial mark; however, a large difference between datum shifts might be an indication of a lack of NGVD 29 leveling (benchmarks) or a problem line. In these cases the option of a survey might be necessary.

The decision tree (fig. 4) should be used as another mechanism to filter gage network datum conversions and evaluate the time and expense to bring the entire network to the NAVD 88 datum. Decision tree outcomes indicating an application of an NGVD 29 to NAVD 88 offset or use of VERTCON are office exercises typically accomplished by data section staff. Surveys are generally cost prohibitive, but may be integrated into operational workflow as follows:

- Establish datum during a new streamgage installation or relocation.
- Establish datum during required routine leveling at streamgages.
- Establish datum at streamgages within the vicinity of scheduled gage maintenance.
- Initiate collaborative efforts among cooperators of the streamgage network that actively conduct surveys such as USACE or the State Department of Natural Resources (DNR) or Department of Transportation (DOT), or water-management districts.



EXPLANATION

Fiducial mark	**Benchmark identified in the datum tie**	n	**Number of instrument setups in a level circuit**
GPS	**Global Positioning System**	offset	**Elevation difference between NGVD 29 and NAVD 88**
GNSS	**Global Navigation Satellite System**	VERTCON	**North American Vertical Datum Conversion tool**
NGS	**National Geodetic Survey**	VDatum	**Vertical datum transformation tool**
IDB	**Integrated database**	TM-3-A19	**U.S. Geological Survey Techniques and Methods, book 3, chapter A19**
NAVD 88	**North American Vertical Datum of 1988**		
NGVD 29	**National Geodetic Vertical Datum of 1929**	TM-11-D1	**U.S. Geological Survey Techniques and Methods, book 11, chapter D1**
√	**Square root**		
M	**Miles out and back in a level circuit**	TWRI-3-A19	**U.S. Geological Survey Techniques of Water-Resources Investigations Report, book 3, chapter A19**

Figure 4. The datum conversion decision tree and survey process.

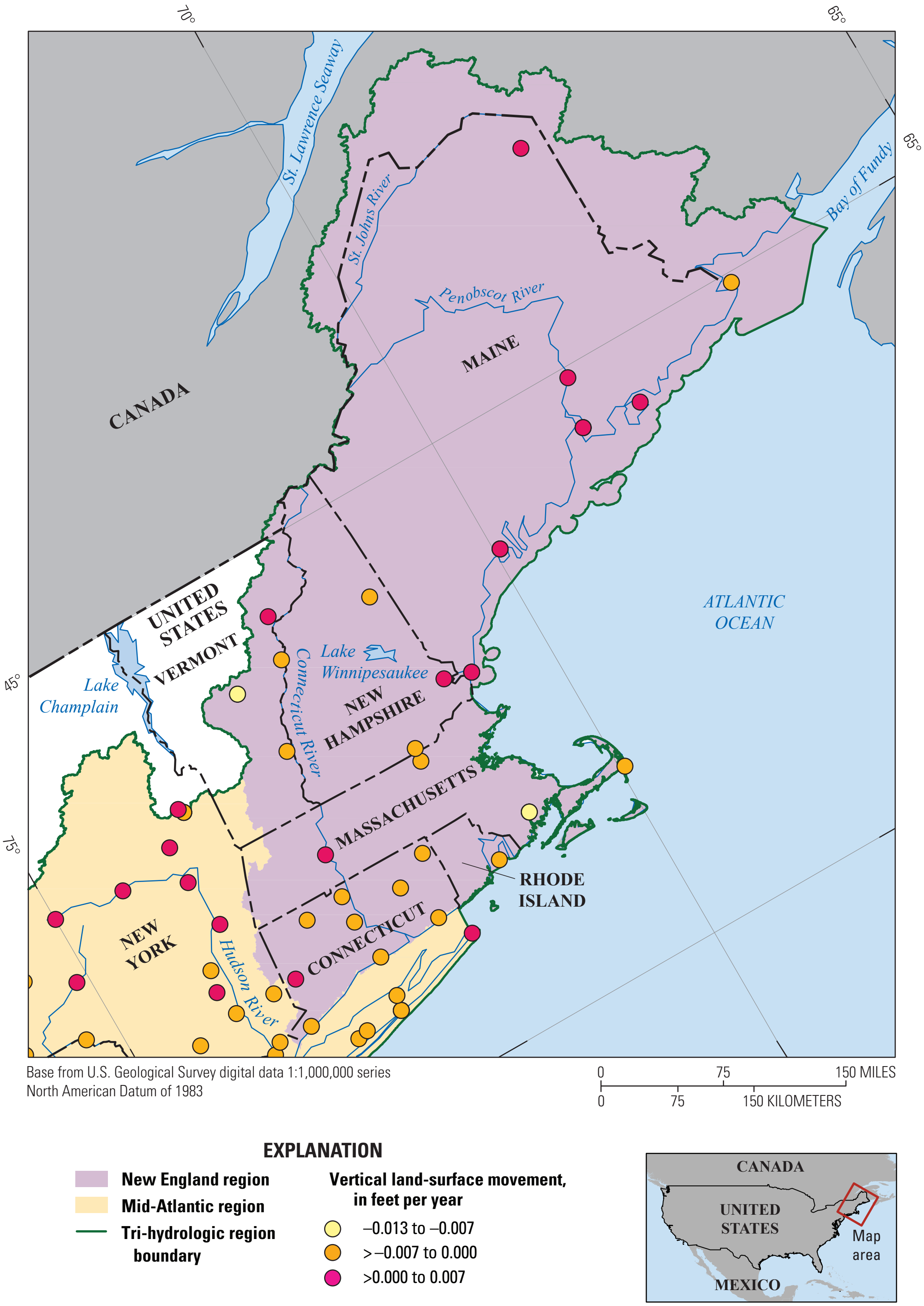


Figure 5. The vertical movement in the New England hydrologic region reflected by published continuously operating reference stations (CORS) during the 2011 update of the National Spatial Reference System (NSRS) (NOAA, 2016a).

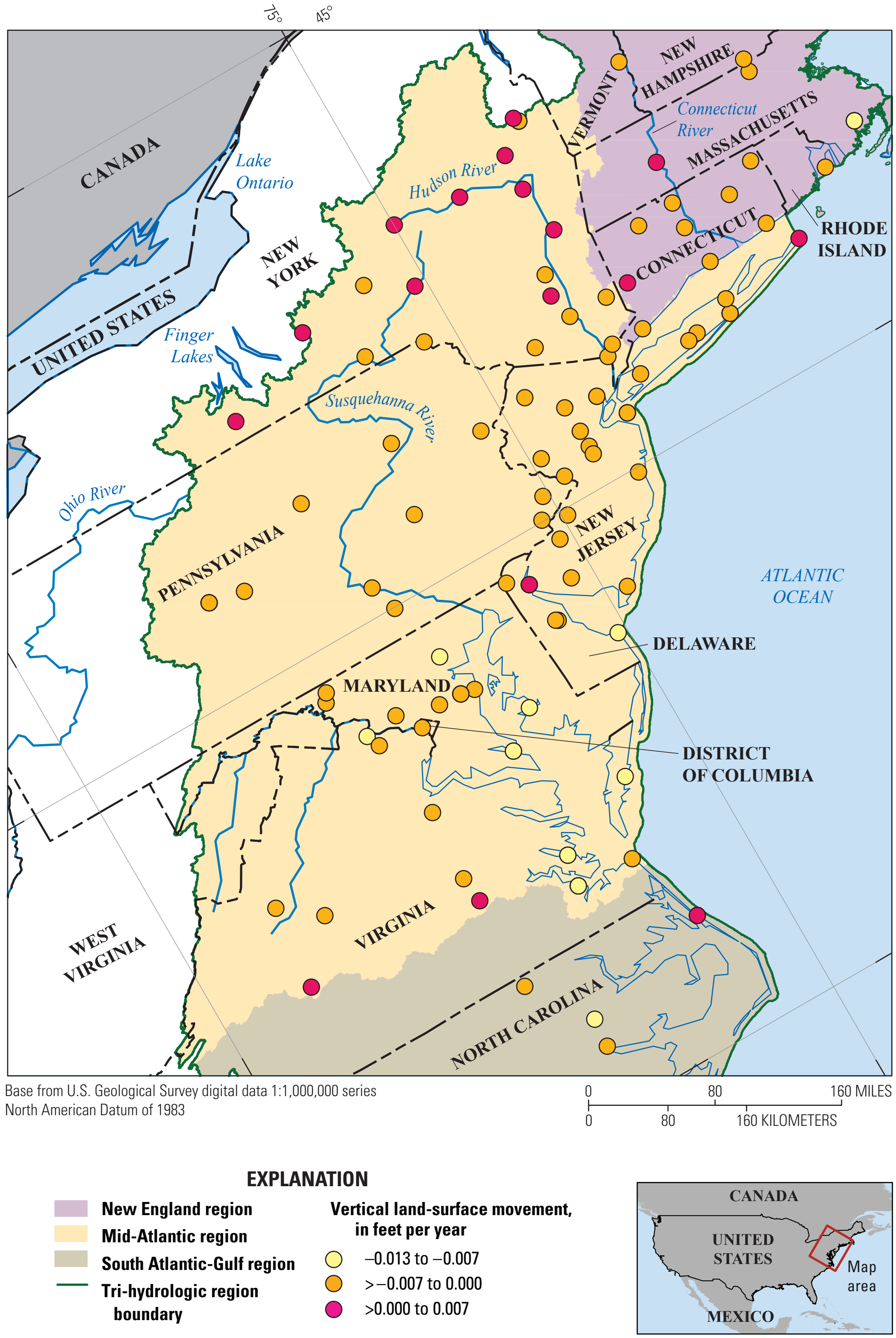


Figure 6. The vertical movement in the Mid-Atlantic hydrologic region reflected by published continuously operating reference stations (CORS) during the 2011 update of the National Spatial Reference System (NSRS) (NOAA, 2016a).

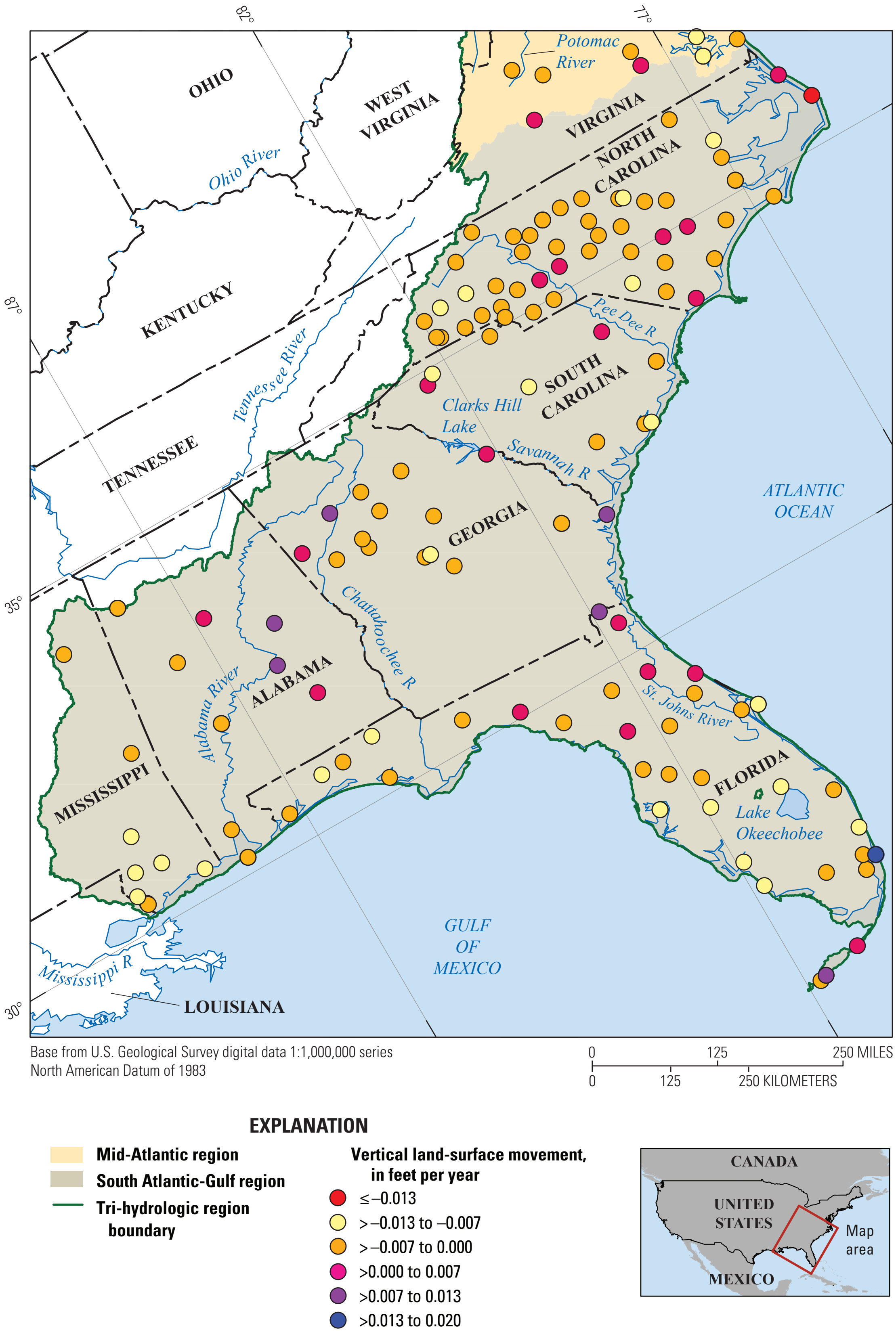


Figure 7. The vertical movement in the South Atlantic-Gulf hydrologic region reflected by published continuously operating reference stations (CORS) during the 2011 update of the National Spatial Reference System (NSRS) (NOAA, 2016a).

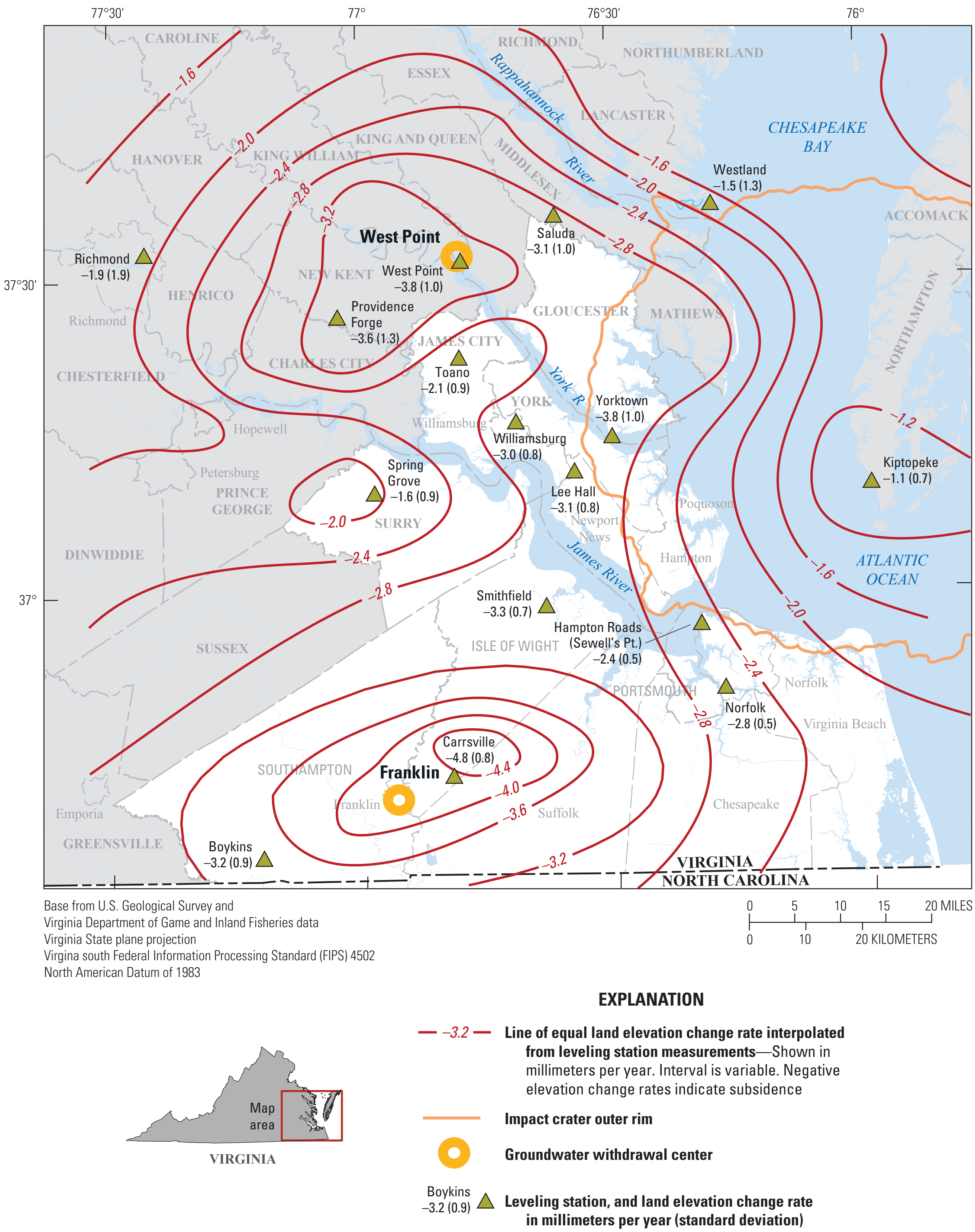


Figure 8. Land elevation change rates from 1940 through 1971 in the Chesapeake Bay area. Adapted from Holdahl and Morrison (1974).

Surveys involve differential and trigonometric leveling as well as GNSS surveying. The decision tree (fig. 4) illustrates the survey approaches and referenced specifications recommended to perpetuate elevation from a fiducial mark to reference marks at the streamgage location or to establish a new fiducial mark by GNSS methods.

Required datum conversions may not be limited to specific locations such as streamgages and may span large areas representing various topographic detail. For topographic datasets that span large areas, a spatially averaged conversion factor may be developed for the dataset, but caution should be exercised in the process because distortions as high as 30 ft may exist (NOAA, 2011b). The process is outlined in the following steps (NOAA, 2011b):

1. Identify the USGS 7.5-minute, 1:24,000-scale topographic quadrangle series maps that are spanned by the topographic dataset.
2. Record the latitude and longitude of the corners of each USGS 7.5-minute quadrangle identified in step 1.
3. Determine the datum shift (NGVD 29 to NAVD 88) using VERTCON for each corner point determined in step 2.
4. Compute the average of the datum shifts for all corner points and the absolute value difference between the average conversion factor and the conversion factor for each corner point.

If the maximum difference between the average datum shift and the datum shift for each corner point is less than 0.25 ft, then the average datum shift shall be applicable to all points within the area spanned by the USGS 7.5-minute quadrangle.

Datum Uncertainty Requirements for U.S. Army Corps of Engineers (USACE), Federal Emergency Management Agency (FEMA), and the National Oceanic and Atmospheric Administration (NOAA)–National Weather Service (NWS)

At the time of this writing, the comprehensive evaluation of project datum (CEPD) is the most current guidance from the USACE for proper application of vertical datums used to reference flood control structure elevations or excavated depths in navigation projects (USACE, 2009). Guidance from CEPD identifies a benchmark requirement within 10 miles of a project as well as a published reference benchmark a short distance from a river gage (USACE, 2009). The current nominal target uncertainty standard has been defined as ±0.25 ft for connecting USACE primary control benchmarks to NSRS. An uncertainty of ±0.25 ft is a relative uncertainty to the NSRS network of survey control and is expressed at the 95 percent confidence level. Third-order standards provided by CEPD (USACE, 2007, 2012) are similar to USGS topographic standards (Staack, 1938) and ensure a closure error limit of $0.05\sqrt{M}$, where M is measured in miles out and back in a level circuit. For gaging stations, USACE identifies a minimum establishment of three benchmarks, where at least one mark is connected to the NSRS (±0.25 ft) and the remaining marks are surveyed to third-order leveling standards (USACE, 2009).

A higher order of relative uncertainty is stated for some USACE projects involving elevation difference uncertainties not achievable by some GNSS methodologies (USACE, 2009). Projects such as this exist in high subsidence regions or involve critical flood control structures. Primary project survey control benchmarks used in these circumstances should maintain a relative uncertainty of ±0.10 ft expressed at the 95 percent confidence level and follow NGS recommendations (Zilkoski and others, 2008) for GNSS-derived vertical control. For project requirements less than ±0.10 ft (USACE, 2009), second-order differential leveling standards (USACE, 2007) are directed, which are similar to USGS topographic standards (Staack, 1938) representing a closure error limit of $0.035 \text{ ft}\sqrt{M}$ as noted previously.

One of the primary components of the Federal Emergency Management Agency (FEMA) mission is regulatory oversight of the National Flood Insurance Program (NFIP), a program designed to reduce the impact of flooding on private and public structures (FEMA, 2016). Flood insurance studies are a byproduct of the NFIP, subject to specifications and guidelines established by FEMA to quality assure (validate) ground surveys and mapping for a variety of spatial products. FEMA guidelines state an uncertainty of ±0.16 ft for establishment of vertical control for field surveys and checkpoint surveys used to quality assure digital elevation datasets developed from photogrammetry or light detection and ranging (lidar; FEMA, 2002). This uncertainty is recommended with GNSS-derived control, referenced to Zilkoski and others (2008) at the 95 percent confidence level. FEMA guidelines also allow the third-order standard (closure error limit $0.05 \text{ ft}\sqrt{M}$) for differential or trigonometric leveling for short distances during field surveys or for checkpoint survey locations in forested areas that need to be extended from a temporary GNSS-derived (±0.16 ft uncertainty) control point established with suitable satellite observation.

Operationally the NWS defines flood impacts at or near gaging locations to correlate stage to inundation or as an impact of local infrastructure. Stage values from USGS gages are identified at critical locations, such as the top of floodgates or levees, low points in roadways, parking lots, or first-floor elevations of commercial businesses. In addition, the NWS has some limited maintenance gaging networks, such as wire-weight gages, throughout the United States to support single-point forecasts. Defining flood impacts and maintaining a point forecast at a wire-weight gage requires differential leveling, which is often conducted by the NWS or by a city or county surveyor. There is no written policy regarding survey tolerance for wire-weight gages; however, the NWS does have the ability to record to a 0.01 ft level of precision within an operational database that stores the zero gage elevation and datum (K. Lander, NOAA National Weather Service, written commun., 2016). Although there are no firm standards for establishing or maintaining gage datums, because the NWS abides by an agency policy that the gage owner (often the USGS) establishes and maintains the datum (NOAA, 2011a), river forecasts are issued to ±0.10 ft, which may be inferred as a datum requirement (K. Lander, NOAA National Weather Service, written commun., 2016). Datum uncertainty may be summarized in the range of ±0.10 to ±0.25 ft among Federal cooperators USACE, FEMA, and NWS (table 7) and should be used as a guide for datum survey efforts tied to USGS gaging operations and resulting elevation standards.

NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) manages a permanent observation network of water-level stations known as the National Water Level Observation Network (NWLON) used for navigation, recreation, and coastal ecosystem management (NOAA, 2016f). The NWLON provides national standards for tide and water-level reference datums used for nautical charting, coastal engineering, international treaty regulation, and boundary determination (NOAA, 2016f). A NWLON primary water-level station requires a stable network of 10 benchmarks, at least three of which represent a Class B stainless steel deep rod, detailed and classified by Floyd (1978). Maintenance of the primary water-level station requires annual leveling to at least one primary benchmark and five additional marks using second-order class I standards and procedures defined by FGCS (1984). By definition, second-order class I specification involves the use of Invar rod construction and requires a foresight (FS) and backsight (BS) distance balance within 16 ft per section, not to exceed 32 ft overall for multiple station setups. A comparison between calibration and field procedure leveling standards among NWLON primary water-level stations and USGS gaging stations is provided in table 8.

Table 7. Comparison of datum uncertainty requirements at the 95 percent confidence level among the U.S. Army Corps of Engineers (USACE), Federal Emergency Management Agency (FEMA), and the National Oceanic and Atmospheric Administration–National Weather Service (NOAA–NWS).

Agency	Datum uncertainty (feet)
USACE	[1]±0.25
FEMA	±0.16
NOAA–NWS	[2]±0.10

[1]±0.10 for higher order relative uncertainty projects.

[2]Inferred without defined confidence level for river forecast levels.

Table 8. Comparison of calibration and field procedure leveling standards: levels at U.S. Geological Survey gaging stations and second-order class I standards.

[FGCS, Federal Geodetic Control Subcommittee; ft, foot; √, square root; *n*, number of station setups; D, distance in kilometers; FS, foresight; BS, backsight; —, undefined]

Standard	U.S. Geological Survey gaging stations (Kenney, 2010)	Second-order class I standards (FGCS, 1984)
Maximum collimation error (ft/100 ft)	|0.003|	|0.005|
Maximum time interval (days) between collimation error determinations	7	1
Rod level verticality maintained within (ft)	10	10
Maximum site length (ft)	164	197
Maximum ground clearence line of site (ft)	1.6	1.6
Maximum circuit misclosure (circuit-closure error limit) (ft)	$\|0.003\sqrt{n}\|$	$\|0.020\sqrt{D}\|$
Rod construction	Wood or metal	Invar
FS and BS distance balance per section (ft)	—	16
Multiple setup accumulated FS and BS distance balance (ft)	—	32

Migration Planning and Publishing of Datum Changes

Oversight and control of datum conversion or datum change are afforded at the local USGS Water Science Center (WSC) level; however, implications may be far reaching to the cooperative water community and general public. The impacts of a datum change at inland and coastal gages are time sensitive among cooperating agencies such as NWS and CO-OPS as well as to USACE as a result of daily forecasting and water-control operations. In addition to forecasting and water-control operations, deterministic flood-inundation mapping has gained momentum over the past decade as another time-sensitive operational product available by NWS and USGS. Probabilistic flood-insurance studies generated by FEMA generally are not as time sensitive as forecasting products, but mapping products are heavily dependent on accurate elevations. Regardless, it is incumbent upon WSC staff to ensure appropriate planning, collaboration, and communication outside the WSC, along with appropriate dissemination of datum changes.

Coordination and Processing

Streamgage datum maintenance is important for hydrologic operations that provide information for Web pages, Rich Site Summary Web feeds, or Geographic Information System products by NWS. Changes to the gage datum may affect existing national, regional, and local databases (NOAA, 2011a), specifically for a change in gage zero datum (opposed to geodetic datum), often tied to forecasting and impact statements. Gage datum disseminated by the NWS is a reflection of datum used by the entity operating the streamgage. As a result, communication is essential between the USGS and the NWS-Weather Forecast Offices and River Forecast Centers for datum updates or conversions.

There are three situations or cases where NWS products and information provided through the Internet would be affected to varying degrees by the conversion of datum from NGVD 29 to NAVD 88 (NOAA, 2011a). Case A is representative of gaging locations where river observations are reported as gage height or stage values above gage zero. For this case, stage values are not affected because they are still reported as heights above the gage zero datum; however, a change in geodetic datum—the assigned elevation of the gage—has implications regarding elevation-sensitive applications such as hydraulic modeling and inundation mapping (NOAA, 2011a). The USGS Office of Surface Water (OSW) Technical Memorandum 2013.02 requires a 90-day notice for a gage zero datum change to allow NWS adequate time to post public notices for forecast products (U.S. Geological Survey, 2013). Although OSW Technical Memorandum 2013.02 pertains to a gage zero datum change, a minimum 30-day notification for a geodetic datum change is suggested because local service change notifications are generally recommended by NWS at least 30 days before revision (NOAA, 2011a). Updates required by the NWS involve changing the “Gage 0” datum (nomenclature identified on the Advanced Hydrologic Prediction Service [AHPS] Web-based hydrographs) along with all affected values in the “about this location” table in AHPS for case A.

Case B involves gaging stations that report stage values as an elevation above a geodetic datum. An applied datum conversion (NGVD 29 to NAVD 88) will affect all observations reporting river, pool, or tailwater conditions. The implication of this change involves the following NWS revisions (NOAA, 2011a):

- “Gage 0” datum in AHPS-disseminated hydrographs
- “About this location” table in AHPS
- All historical crests and low-water records
- All flood impact and low-water impact information

NWS identifies case B as a substantial change, affecting product content and automated parsing, and requires a service change of 120 days (NOAA, 2011a). An addendum to OSW Technical Memorandum 2013.02, allowing a minimum notification of 120 days (opposed to 90 days), should be required for case B datum conversions.

A case C datum change is essentially twofold, a combination of both case A and case B, involving a change from gage zero datum observations to observations reported as elevations above a geodetic datum and geodetic-based observations to be converted from NGVD 29 to NAVD 88. These changes are more complex and require collaboration to assure NWS revisions similar to case B, with the addition of converting historical information from NGVD 29 to elevation-based gage heights in NAVD 88 (NOAA, 2011a). A notification similar to case B of 120 days should be required for a case C datum change.

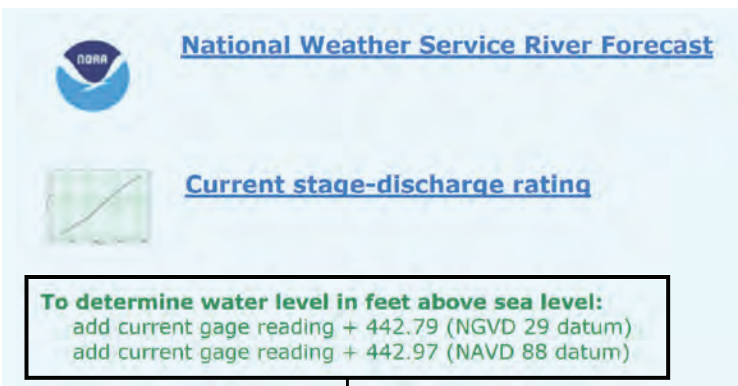
In all cases, datum conversions or datum change should be well communicated among the cooperative water community, more specifically with NWS, CO-OPS, and USACE. Datum change notification times described above for case scenarios A, B, and C are suitable for NWS, CO-OPS, and USACE, assuring closer collaboration and consistency among data, forecasting, and water-control operations.

Dissemination

Table 5 defines the availability of geodetic vertical datum to be stored in GWSI. Although a variety of geodetic vertical datum may be stored in GWSI, at the time of this writing only one datum can be disseminated and, therefore, queried by way of NWIS. From within the NWIS (GWSI) software, users can query all of the datum history records; users outside of the USGS, however, will only see one datum because NWISWeb displays only one. Knowing the offset between NGVD 29 and NAVD 88 is important for projects and water-control operations within USACE or other legacy information from agencies still in transition between geodetic datums. Dissemination of two vertical datums, whether NGVD 29 and NAVD 88 or another legacy datum and NAVD 88, eases the migration of datum conversion or datum change among forecasting and water-control operations within NWS and USACE by providing a frame of reference for both current and legacy information. Until the functionality exists to disseminate two vertical datums through NWIS, many WSCs disseminate conversions directly on the inland or coastal NWIS gage station page (fig. 9) or simply archive and disseminate a list of both datums or conversions to cooperators from the local WSC office. Dissemination of both NGVD 29 and NAVD 88 as illustrated in figure 9 involves accessing the USGS internal directory structure of NWISWeb located at /usr/opt/nwisweb as found in the NWISWeb manual (http://waterdata.usgs.gov/nwis/?nwisweb_manual_nwis.html) at the time of this writing. From the NWIS-side processing, the pathname is further expanded to the "nwis_host" directory and subsequent local directories to access a text file that is added to the NWISWeb Hyper Text Markup Language (HTML) page as shown in the example in figure 9.

Referring to OSW Technical Memorandum 2013.02, changes to gage datum should also be documented by assuring entry of historic datum into the datum history (table 3). At a minimum, this information provides a needed chronology to query and reference historic hydrologic information.

National Water Information System (NWIS) Web *Screen Capture*



Hypertext Markup Language (HTML) coding attribute

```
<br clear="all" />
  <p style="font-size:small; color:green;">
  <strong>  To determine water level in feet above sea level:
  </strong><br />
  <span style="margin-left:30px;">
  add current gage reading + 442.79 (NGVD 29 datum)
  </span>
  <br />
  <span style="margin-left:30px;">
  add current gage reading + 442.97 (NAVD 88 datum)
  </span>
  </font>
 </p>
 <br clear"all" />
 </div>
 <br />
```

Figure 9. Dissemination of both National Geodetic Vertical Datum of 1929 (NGVD 29) and North American Vertical Datum of 1988 (NAVD 88) at a gaging location as illustrated through the National Water Information System (NWIS) Web with Hypertext Markup Language (HTML) coding attribute.

Gravity for the Redefinition of the American Vertical Datum (GRAV-D)

The North American Vertical Datum of 1988 (NAVD 88) is the current vertical datum for the United States that is based on the height of the primary tidal benchmark that represents local mean sea level at Father Point/Rimouski, Quebec, Canada (NOAA, 2015c). This datum cannot be maintained or perpetuated by the NGS because it is based on passive, terrestrial monuments that are not regularly checked for movement and are often destroyed by construction (NOAA, 2007). Gravity measurements that support the NAVD 88 are out of date and do not represent the Earth's current gravity field. The accuracy of the NAVD 88 is expected to decrease over time because there is no large-scale tracking of gravity changes due to crustal deformation and movement from processes like subsidence, post-glacial rebound, and crustal motion. Additionally, because the NAVD 88 was determined by conventional leveling methods from a single point, it is prone to propagation of error as a function of distance from the origin. The buildup of error from conventional leveling created an approximate 3-ft tilt from southeast (Florida) to northwest (Washington) across the contiguous United States when compared to the latest gravimetric geoid model (NOAA, 2015c).

Global Navigation Satellite System observations are measurements of ellipsoidal heights, which are converted to orthometric heights using a hybrid geoid model that is currently based on a network of terrestrial benchmarks (Henning, 2010; Rydlund and Densmore, 2012). Therefore, the accuracy of GNSS-derived orthometric heights are inherently tied to the accuracy of the geoid model from which they are derived. The NGS (NOAA, 2001) defines a geoid as the equipotential surface of the Earth's gravity field, which best fits, in a least squares sense, global mean sea level. A need exists to produce a new geoid model that is representative of the Earth's dynamic gravity field. A static geoid model that is not updated over time to represent the Earth's current gravity field will reduce the accuracy of GNSS-derived orthometric heights.

In 2007, the NGS started work on the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project that models and monitors the surface of the Earth's gravity field (geoid) for the purpose of improving how elevations (heights) are determined in the United States and its territories (NOAA, 2010). One of the goals of the GRAV-D project is to replace the current vertical datum of the United States with a new gravity-based, geopotential datum that references a gravimetric geoid accurate at the 0.033 ft level by 2022 (NOAA, 2016d). The new datum will be realized by determining ellipsoidal heights using GNSS and then removing the gravimetric geoid to arrive at the orthometric height at the point of interest in the new datum (NOAA, 2013).

Expected Uncertainties

The NGS has set a goal of centimeter-level (0.033 ft) accuracy for the gravimetric geoid (NOAA, 2015c); however, the geoid will be difficult to model in mountainous area such as the Alaskan Range and the Rocky Mountains because of sparse surface gravity measurements and increased noise in the airborne gravity data (NOAA, 2013). Conversely, the NGS expects to meet the 0.033 ft level accuracy goal near areas with lower-relief topography and more reliable surface gravity data. For both scenarios, the accuracy of the new datum will be much improved over NAVD 88. Orthometric heights resulting from GNSS that reference the gravimetric geoid will be accurate at the 0.066 ft level (0.033 ft derived from the geoid model, and 0.033 ft derived from GNSS; NOAA, 2015c).

Implication of a NAVD 88 Conversion

The NGS plans to implement the gravity-based vertical datum by 2022, which will become official pending approval by the FGCS (NOAA, 2015a). The Office of Management and Budget Circular No. A–16 (Office of Management and Budget, 2002) will require all Federal and State agencies to transition to the new vertical datum; local agencies and private sector companies may convert to the new vertical datum as appropriate.

The predicted change from the NAVD 88 to the gravity-based, geopotential datum can be estimated by subtracting the gravimetric geoid model (USGG 2009) from the existing NAVD 88 surface (fig. 10). The predicted change is variable across the contiguous United States, which ranges from approximately greater than –3.4 ft (–1.04 meters [m]) in the northwestern part of the country near the State of Washington to greater than 0.0 ft (0.00 m) near southern Florida. The average expected change is approximately –1.6 ft (–0.50 m), with an approximate 3 ft (1 m) tilt (CONUS tilt) from southeast to northwest, as described above (NOAA, 2015a). The contiguous United States (CONUS) tilt is the suspected amount of uncertainty (described above) in the network of NAVD 88 benchmark heights in the lower 48 States that is made up of three components: (1) orthometric heights determined by conventional levels; (2) ellipsoidal heights obtained by GNSS; and (3) gravity data used to determine the geoid model (NOAA, 2013). The latter two components are considered only a fraction of the CONUS tilt error budget because GNSS-derived ellipsoidal heights and measurements from GRACE satellite data that were used (in part) to determine the geoid model are known to be approximately 0.1 ft (0.02 m) over long wavelengths of approximately 125 miles (200 kilometers). Therefore, the remaining error budget can be attributed to cross-country error buildup from conventional levels originating from a single point (NOAA, 2013).

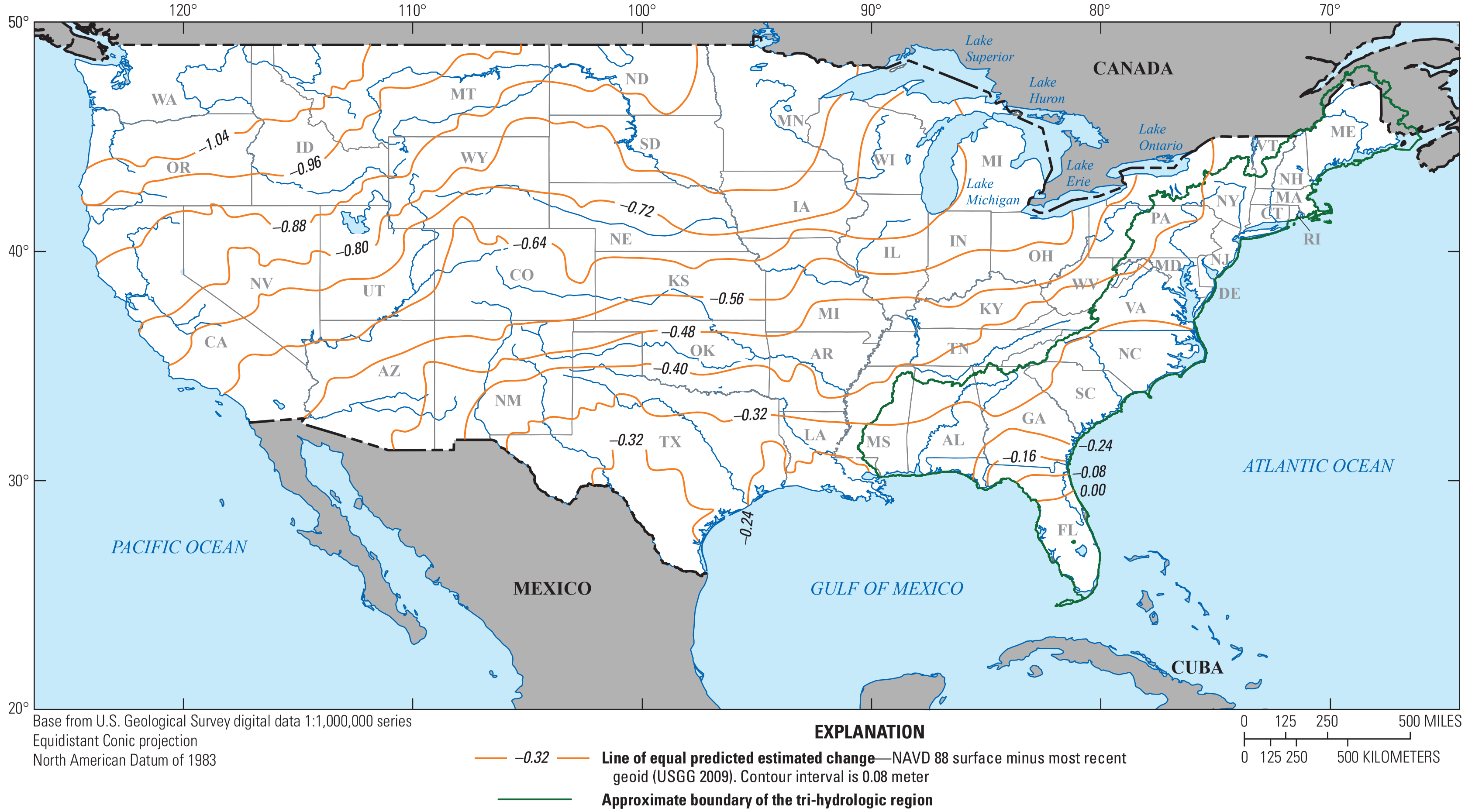


Figure 10. Predicated datum change from the North American Vertical Datum of 1988 (NAVD 88) surface minus the gravimetric geoid (USGG 2009) for the contiguous United States. Modified from NOAA, 2016d.

The estimated predicted change from the geodetic datum (NAVD 88) to geopotential datum for the tri-hydrologic region ranges from approximately less than –1.5 ft (–0.45 m) in the western part of the Mid-Atlantic region, near western Pennsylvania and New York, to a change greater than 0.0 ft (0.00 m) in the southern part of the South Atlantic-Gulf region, near southern Florida (fig. 10). Predicted change estimates were coarsely determined (interpreted) from the contours shown in figure 10. The approximate predicted change for the New England, Mid-Atlantic, and South Atlantic-Gulf regions range from –1.3 ft (–0.40 m) to –1.0 ft (–0.32 m), –1.5 ft (–0.45 m) to –1.0 ft (–0.31 m), and from –1.3 ft (–0.39 m) to greater than 0.0 ft (0.0 m), respectively.

Future Datum Conversion Using GRAV-D

The NGS will provide a conversion surface between NAVD 88 and the new gravity-based geopotential datum for transformation of maps (NOAA, 2013). Datum transformation tools such as VDatum and VERTCON will be updated by the NGS to accommodate conversions from NAVD 88 to the new geopotential datum (NOAA, 2015a). These tools will be merged into a single utility for online browser-based computations and will be available as a geographic information system plug-in application. In anticipation of the new geopotential datum, it is recommended to establish a GNSS single-base static observation (minimum Level II quality standard available for Online Position User Service Database publication or OPUS-DB, Rydlund and Densmore, 2012) at gage locations or fiducial benchmarks because leveled-height-produced benchmarks representing only NGVD 29 and NAVD 88 adjustments will not be available for a direct transformation from NAVD 88 to the new geopotential datum. Gage locations or fiducial benchmarks with leveled-height-only representations will be subject to an indirect datum transformation, representing “modeled” areas similar to locations that were not part of the 381,833 points used to develop the initial VERTCON transformation tool between NGVD 29 and NAVD 88 (D. Martin, National Geodetic Survey, oral commun., 2016).

References Cited

Critigen, 2016, Find-A-Control App, Critigen geospatial systems integrator: Critigen Web page, accessed August 25, 2016, http://www.critigen.com/solution/find-control-app.

Eggleston, Jack, and Pope, Jason, 2013, Land subsidence and relative sea-level rise in the southern Chesapeake Bay region: U.S. Geological Survey Circular 1392, 30 p., accessed June 15, 2016, at https://doi.org/10.3133/cir1392.

Federal Emergency Management Agency [FEMA], 2002, Appendix A, Guidance for aerial mapping and surveying, *in* Guidelines and specifications for flood hazard mapping partners: Federal Emergency Management Agency Flood Hazard Mapping Program, 57 p., accessed June 9, 2016, at ftp://ftp.gilacountyaz.gov/public/publicworks/Floodplain/StateStdsCD/frm_gsaa.pdf.

Federal Emergency Management Agency [FEMA], 2016, The National Flood Insurance Program: Federal Emergency Management Agency, accessed June 8, 2016, at https://www.fema.gov/national-flood-insurance-program.

Federal Geodetic Control Subcommittee [FGCS], 1984, Standards and specifications for geodetic control networks: National Oceanic and Atmospheric Administration, National Geodetic Survey, accessed June 2, 2016, at http://www.ngs.noaa.gov/FGCS/tech_pub/1984-stds-specs-geodetic-control-networks.htm.

Floyd R.P., 1978, Geodetic bench marks: National Oceanic and Atmospheric Administration Manual NOS NGS 1, accessed June 20, 2016, at http://www.ngs.noaa.gov/PUBS_LIB/GeodeticBMs/#section4.5.

Gill, S.K., and Schultz, J.R., eds., 2001, Tidal datums and their applications: National Oceanic and Atmospheric Administration Special Publication NOS CO–OPS 1, 112 p. with appendixes.

Grgić, Ilija, Lučić, Maro, and Kršulović, Davor, 2010, The appliance of trigonometric leveling on long distances: EUREF Symposium, Gävle, Sweden, June 2–5, 2010, accessed June 12, 2016, at http://www.academia.edu/11284066/The_Appliance_of_the_Trigonometric_levelling_on_the_long_distances.

Henning, W.E., 2010, User guidelines for single base real time GNSS positioning: National Oceanic and Atmospheric Administration, National Geodetic Survey, 151 p.

Holdahl, S.R., and Morrison, N.L., 1974, Regional investigations of vertical crustal movements in the U.S., using precise relevelings and mareograph data: Technophysics, v. 23, no. 4, p. 373–390.

Kavanagh, B.F., 2004, Surveying with construction applications: Upper Saddle River, N.J., Pearson Prentice Hall, 658 p.

Kennedy, E.J., 1990, Levels at streamflow gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations Report 3A–19, 39 p.

Kenney, T.A., 2010, Levels at gaging stations: U.S. Geological Survey Techniques and Methods, book 3, chap. A19, 60 p. [Also available at http://pubs.usgs.gov/tm/tm3A19/.]

McCallum, B.E., Wicklein, S.M., Reiser, R.G., Busciolano, Ronald, Morrison, Jonathan, Verdi, R.J., Painter, J.A., Frantz, E.R., and Gotvald, A.J., 2013, Monitoring storm tide and flooding from Hurricane Sandy along the Atlantic coast of the United States, October 2012: U.S. Geological Survey Open-File Report 2013–1043, 42 p., accessed July 28, 2016, at http://pubs.usgs.gov/of/2013/1043/.

Milbert, D.G., 1999, National Geodetic Survey height conversion methodology, VERTCON: National Geodetic Survey Web page, accessed May 30, 2016, at http://www.ngs.noaa.gov/TOOLS/Vertcon/vert_method.html.

National Oceanic and Atmospheric Administration [NOAA], 1993, Affirmation of vertical datum for surveying and mapping activities: Federal Register, v. 58, no. 120, p. 34245 [Docket No. 930650-3150].

National Oceanic and Atmospheric Administration [NOAA], 2001, What is the geoid? The official NGS geoid page: National Geodetic Survey Web page, accessed June 21, 2016, at http://www.ngs.noaa.gov/GEOID/geoid_def.html.

National Oceanic and Atmospheric Administration [NOAA], 2007, The GRAV-D project plan, Gravity for the redefinition of the American Vertical Datum (GRAV-D), accessed June 10, 2016, at http://www.ngs.noaa.gov/GRAV-D/pubs.shtml.

National Oceanic and Atmospheric Administration [NOAA], 2010, How NOAA's GRAV-D project impacts and contributes to NOAA science: National Geodetic Survey Web page, accessed June 10, 2016, at http://www.ngs.noaa.gov/GRAV-D/pubs.shtml.

National Oceanic and Atmospheric Administration [NOAA], 2011a, Hydrologic data network services: National Weather Service, Operations and Services Hydrologic Services Program, NWSPD 10-9, National Weather Service Instruction 10-940, September 28, 34 p., accessed July 28, 2016, at http://www.nws.noaa.gov/directives/sym/pd01009040curr.pdf.

National Oceanic and Atmospheric Administration [NOAA], 2011b, NOAA partnered guidelines for the development of advanced hydrologic prediction service flood inundation mapping: National Oceanic and Atmospheric Administration, prepared by Dewberry, 65 p.

National Oceanic and Atmospheric Administration [NOAA], 2013, Q&As from GRAVD-D and the GSVS surveys—Update on the path to the new vertical datum webinar: National Geodetic Survey Web page, accessed June 15, 2016, at http://www.ngs.noaa.gov/corbin/class_description/QAGRAVDwebinar0213.pdf.

National Oceanic and Atmospheric Administration [NOAA], 2015a, Overview of new datums: A webinar for NGAC and FGDC, accessed June 15, 2016, at http://www.ngs.noaa.gov/web/science_edu/webinar_series/Overview_New_Datums.shtml.

National Oceanic and Atmospheric Administration [NOAA], 2015b, Survey marks and datasheets: National Geodetic Survey Web page, updated September 2016, accessed June 14, 2016, at https://www.ngs.noaa.gov/datasheets/.

National Oceanic and Atmospheric Administration [NOAA], 2015c, Update on GRAV-D and progress toward a new vertical Datum, accessed June 10, 2016, at http://www.ngs.noaa.gov/web/science_edu/presentations_library/.

National Oceanic and Atmospheric Administration [NOAA], 2016a, Computed velocities for Continually Operating Reference Stations: National Oceanic and Atmospheric Administration Web page, accessed September 5, 2016, ftp://geodesy.noaa.gov/cors/coord/coord_08/nad83_2011_geo.comp.txt.

National Oceanic and Atmospheric Administration [NOAA], 2016b, DSWORLD, User-contributed PC software: National Geodetic Survey Web page, accessed August 25, 2016, at http://www.ngs.noaa.gov/PC_PROD/PARTNERS/.

National Oceanic and Atmospheric Administration [NOAA], 2016c, Frequently asked questions: National Geodetic Survey Web page, accessed August 24, 2016, at http://www.ngs.noaa.gov/faq.shtml#WhyVD29VD88.

National Oceanic and Atmospheric Administration [NOAA], 2016d, GRAV-D airborne campaign—Overview, progress, future, accessed June 15, 2016, at http://www.ngs.noaa.gov/web/science_edu/presentations_library/.

National Oceanic and Atmospheric Administration [NOAA], 2016e, How we observe the ocean—Tide gauges: Ocean Climate Observation Program Web page, accessed May 31, 2016, at http://www.oco.noaa.gov/tideGauges.html. Link no work STET?

National Oceanic and Atmospheric Administration [NOAA], 2016f, The National Water Level Observation Network (NWLON): National Water Level Program, Center for Operational Oceanographic Products and Services (CO-OPS), Tides & Currents Web page, accessed June 20, 2016, at http://tidesandcurrents.noaa.gov/nwlon.html.

National Oceanic and Atmospheric Administration [NOAA], 2016g, NOAA manages the National Spatial Reference System: National Geodetic Survey, accessed June 6, 2016, at http://www.ngs.noaa.gov/INFO/OnePagers/NSRSOnePager.pdf.

National Oceanic and Atmospheric Administration [NOAA], 2016h, Tidal datums: Tides & Currents Web page, accessed June 23, 2016, at https://tidesandcurrents.noaa.gov/datum_options.html.

National Oceanic and Atmospheric Administration [NOAA], 2016i, A tutorial on datums: National Oceanic and Atmospheric Administration, Vertical Datum Transformation, accessed May 23, 2016, at http://VDatum.noaa.gov/docs/datums.html.

Nestorović, Žarko, and Siniša, Delčev, 2014, Comparison of height differences obtained by trigonometric and spirit leveling methods: Geonauka, v. 2, no. 4, 8 p., accessed June 16, 2016, at https://doi.org/10.14438/gn.2015.01.

Norris, J.M., 2010, U.S. Geological Survey streamgage operation and maintenance cost evaluation: U.S. Geological Survey Fact Sheet 2010–3025, 2 p., accessed July 20, 2016, at http://pubs.usgs.gov/fs/2010/3025/.

Office of Management and Budget, 2002, Coordination of geographic information and related spatial data activities (revised): Office of Management and Budget Circular No. A–16, accessed September 5, 2016, at https://www.whitehouse.gov/omb/circular_a016_rev.

Ogundare, J.O., 2015, Precision surveying—The principles and geomatics practice: John Wiley & Sons, Inc., 648 p.

Rydlund, P.H., Jr., and Densmore, B.K., 2012, Methods of practice and guidelines for using survey-grade global navigation satellite systems (GNSS) to establish vertical datum in the United States Geological Survey: U.S. Geological Survey Techniques and Methods, book 11, chap D1, 102 p. with appendixes, accessed July 19, 2016, at http://pubs.usgs.gov/tm/11d1/.

Seaber, P.R., Kapinos, F.P., and Knapp, G.L., 1987, Hydrologic unit maps: U.S. Geological Survey Water-Supply Paper 2294, 63 p., accessed July 19, 2016, at http://pubs.usgs.gov/wsp/wsp2294/.

Staack, J.G., 1938, Spirit leveling in Missouri, 1896–1938: U.S. Department of the Interior, Geological Survey, Bulletin 898–C, 450 p.

U.S. Army Corps of Engineers [USACE], 2007, Engineering and design, Control and topographic surveying: Department of the Army, U.S. Army Corps of Engineers, Engineer Manual 1110–1–1005, 498 p.

U.S. Army Corps of Engineers [USACE], 2009, Engineering and design, Comprehensive evaluation of project datums: Department of the Army, U.S. Army Corps of Engineers, Engineer Circular 1110–2–6070, 150 p.

U.S. Army Corps of Engineers [USACE], 2012, Engineering and design, Geospatial data and systems: Department of the Army, U.S. Army Corps of Engineers, Engineer Manual 1110–1–2909, 224 p.

U.S. Geological Survey [USGS], 2004, User's manual for the National Water Information System of the U.S. Geological Survey, Ground-Water Site-Inventory System: U.S. Geological Survey Open-File Report 2004–1238, ver. 4, 275 p.

U.S. Geological Survey [USGS], 2013, Requirement for 90-day notification period prior to gage datum changes at streamgages: U.S. Geological Survey, Office of Surface Water Technical Memorandum 2013.02, accessed July 20, 2016, at https://water.usgs.gov/admin/memo/SW/sw13.02.html.

U.S. Geological Survey [USGS], 2016a, National Water Information System—Web interface, accessed May 29, 2016, at https://doi.org/10.5066/F7P55KJN.

U.S. Geological Survey [USGS], 2016b, USGS Flood Event Viewer—Providing hurricane and flood response data: U.S. Geological Survey flood information Web page, accessed July 14, 2016, at https://water.usgs.gov/floods/FEV/.

U.S. Geological Survey [USGS], 2016c, Coastal Storm Response Surge, Wave, and Tide Hydrodynamics Network (SWaTH): U.S. Geological Survey, accessed July 14, 2016, at https://www.sciencebase.gov/catalog/item/560aa95ce4b058f706e5374b.

Zilkoski, D.B., Carlson, E.E., and Smith, C.L., 2008, Guidelines for establishing GPS-derived orthometric heights: National Geodetic Survey, National Oceanic Atmospheric Administration (NOAA) Technical Memorandum NOS NGS 59, 19 p.

Zilkoski, D.B., Richards, J.H., and Young, G.M., 1992, Results of the general adjustment of the North American Vertical Datum of 1988: American Congress on Surveying and Mapping, Surveying and Land Information Systems, v. 52, no. 3, p. 133–149.

Glossary

accuracy The degree to which measurements derived from static or real-time positioning represents "truth." Trusted monuments, as compared with GNSS positioning, are often used to evaluate accuracy during a campaign.

active stations (active control or monumentation) A receiver and GNSS antenna in a fixed location that are continually operating and collecting data. Continually operating reference stations (CORS) are active control stations.

adjustment Processing of a value or dataset to provide a precise or accurate result based on the inclusion of control data using the process of least squares. Adjustments are used in network surveys involving static data collection.

Antenna Reference Point (ARP) A point on the exterior of the antenna to which the National Geodetic Survey references the antenna phase center position. Typically the bottom of the antenna mount.

Continually Operating Reference Stations (CORS) A network of continually operating reference stations that provide Global Navigation Satellite System (GNSS) data consisting of carrier phase and code range measurements in support of three-dimensional positioning, meteorology, space weather, and geophysical applications through the United States, its territories, and a few foreign countries.

control point A benchmark representing assigned coordinates by terrestrial or satellite surveying techniques.

crustal motion Changes in time of the position and height of the Earth plates.

datum In geodetic terms, the datum is defined by its reference surface, an origin, an orientation, gravity, and a scale. The North American Datum of 1983 (NAD 83) is defined by the Geodetic Reference System of 1980 (GRS 80) ellipsoid, at an origin near the center of the mass of the Earth, with axes oriented through the equator and at right angles, with a scale unit based on the international meter. The realization of this datum is through a reference such as monumentation on the ground or GNSS satellites with the ground control segment.

Dilution of Precision (DOP) An indicator of satellite geometry quality for a unique constellation. Poor satellite geometry leads to poor DOP and poor triangulation and location estimation. A low DOP value represents a better positional precision due to wide angular separation between the satellites used to calculate a terrestrial position.

DSWorld Application used to display geodetic information by way of National Geodetic Survey datasheets in a world view through Google Earth.

ellipsoid height The height above or below a mathematically defined surface or ellipsoid (for example, Geographic Reference System 1980 (GRS 80) or World Geodetic System 1984 (WGS 84) that provides a representation of the Earth, flattened slightly at the poles, and bulging somewhat at the equator. The height coordinate determined by a GNSS observation is related to the surface of the ellipsoid, typically WGS 84.

fiducial Accepted as an origination or standard of reference.

Find-A-Control Application that accesses the National Geodetic Survey Integrated Database (NGS-IDB) through a mobile field device.

geodetic survey Surveys conducted for the establishment of control networks, which are the basis for accurate positioning and navigation. These surveys account for refraction, curvature of the Earth, atmospheric conditions, and gravity as opposed to "plane" surveys that generally ignore these considerations.

geoid The equipotential surface of the Earth that most closely approximates global mean sea level.

Global Navigation Satellite System (GNSS) A satellite navigation system with global coverage.

HyperText Markup Language (HTML) Markup language describing Web documents (Web pages) by a series of tags.

International Terrestrial Reference Frame (ITRF) Realizations of the International Terrestrial Reference System (ITRS) for a particular epoch in time, consisting of a set of three-dimensional coordinates and velocities for hundreds of geodetic stations located around the world. Examples of reference frames: ITRF94, ITRF96, ITRF97, ITRF2000, ITRF2005, and ITRF2008.

International Terrestrial Reference System (ITRS) The most precise, geocentric, and globally defined coordinate system or datum of the Earth. This system is managed by the International Earth Rotation and Reference Systems Service (IERS) located in Frankfurt, Germany.

localization (site calibration) A vertical shift applied to match a single elevation or planar surface. The user should assure trusted benchmarks that are used to apply the vertical shift.

monumented benchmarks Monumented benchmarks have a tablet with identifying information surrounding a stamped center point. These marks are represented as a standard metal tablet, disk, cap, or steel rod used to describe the elevation. These tablets are commonly set in concrete, stone posts, firm rock outcroppings, masonry structures, and buildings. Feno markers are also considered monumented benchmarks.

NAD 83 The North American Datum of 1983. The official national horizontal datum for the United States depicted as a three-dimensional datum with coordinates of points expressed in latitude, longitude, and ellipsoid height. The NAD 83 origin is near the center of mass of the Earth.

NAVD 88 The North American Vertical Datum of 1988. Established in 1991 and referenced to the International Great Lakes Datum of 1985, local mean sea level height at Father Point/Rimouski, Quebec, Canada.

non-monumented benchmarks Non-monumented benchmarks may be considered semi-permanent monumentation that consists of chiseled squares; crosses or circles on concrete or masonry structures; bolt heads in steel, concrete, or masonry structures; and metal pins or magnetic (mag) nails in concrete or asphalt. Non-monumented benchmarks are simply a mark with no identifying information.

objective point Typically thought of as a foresight regarding terrestrial surveying. The “established” point in a GNSS survey.

Online Position User Service (OPUS) A software service by the National Geodetic Survey providing access to the National Spatial Reference System (NSRS) to derive coordinates from the CORS network.

orthometric height The height of a point on the Earth’s surface, measured as a distance along a curved plumb line and normal to gravity from the reference surface to that point. Heights above or below the datum can be obtained through GNSS methods by using the current hybrid geoid model and NAD 83 ellipsoid heights.

passive stations (benchmarks) Referred to as a traditional ground station such as a benchmark. Passive stations are those that can be occupied by survey equipment.

position The three-dimensional coordinate of a point, typically given in the form of latitude, longitude, and ellipsoid height. An estimate of error is often given with a position.

postglacial rebound Rise of land masses that were depressed by the huge weight of ice sheets during the last glacial period.

precision The degree of repeatability that measurements of the same quantity display. A description of the quality of the data with respect to random errors. Precision is traditionally measured using standard deviation and may be thought of as the spread of the positional error.

realization A physical, usable manifestation of a particular datum. Realizations or alignments are typically conducted on benchmarks with published coordinates as found in the NGS-IDB or by locally set monuments; however, active monumentation can also serve as the basis for a realization.

Real-Time Kinematic, Single Base (RTK) A traditional relative positioning procedure whereby observables and corrections for each L_1 and L_2 signal to each common satellite are transmitting in real time from a base station to the user's rover receiver. The rover receiver processes the data in real time. Centimeter level accuracy is achieved without any post processing.

real-time network A statewide-based network of continuously operating reference stations that are municipally, State, and privately owned. A centralized server is used to facilitate quality-assurance checks, network modeling, estimation of systematic errors, and calculation of corrected data that are submitted back to the end user at the rover position. The network operates by use of cellular communication that excludes the requirement for a traditional base station to be used in the field.

reference station (base station) A ground station at a known location used to derive differential corrections. The reference station receiver tracks all satellites in view, corrects pseudo-range errors, and then transmits the corrections with the carrier-phase observables to the rover.

root mean square (RMS) Mathematically, the square root of the average of the sum of the squared residuals from the computed value. Regarding the solution, RMS is a measure of predictive power depicted as a spread of the results. For real-time (RT) positioning, RMS error typically is expressed as x, y, and z (up), at the 68 percent confidence level. These values should be doubled to express at the 95 percent confidence level.

total station An electronic theodolite (transit) integrated with an electronic distance meter to read slope distances from the instrument to a particular point.

subsidence The gradual caving in or sinking of an area of land.

trilateration A method of determining a relative terrestrial position using the geometry of three-dimensional spheres from satellite locations and the terrestrial location. This mathematical principle ultimately makes the calculation knowing the location of at least three satellites above the terrestrial location and the distance between the terrestrial location and the satellites.

uplift Geological reference to the vertical elevation of the Earth's surface in response to natural causes.

World Geodetic System 1984 (WGS 84) A global geodetic datum defined and maintained by the Department of Defense. Control segments and broadcast ephemerides are expressed in this datum; as a result, GNSS positioning results are referenced to this datum. WGS 84 positions differ from NAD 83 positions by 1 to 2 meters.

Manuscript approved February 6, 2017

Prepared by the USGS Science Publishing Network
Reston and Denver Publishing Service Centers
Edited by Kay P. Naugle
Illustrations by Jeffrey Corbett
Cover design by Carol Quesenberry
Layout by Caryl J. Wipperfurth

For additional information regarding this publication, please contact:
Director, Missouri Water Science Center
U.S. Geological Survey
1400 Independence Road, MS 100
Rolla, MO 65401
(573) 308-3667

Or visit the Missouri Water Science Center website at
https://mo.water.usgs.gov/

Rydlund and Noll—**Vertical Datum Conversion Process for the Inland and Coastal Gage Network in the Tri-Hydrologic Region**—Techniques and Methods 11-B8 ver. 1.1

ISSN 2328-7055 (online)
https://doi.org/10.3133/tm11B8