Chapter 4

The National Elevation Dataset

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INTRODUCTION

The National Elevation Dataset (NED) is the primary elevation data product produced and distributed by the U.S. Geological Survey (USGS). Since its inception, the USGS has compiled and published topographic information in many forms, and the NED is the latest development in this long line of products that describe the land surface. The NED provides seamless raster elevation data of the conterminous United States, Alaska, Hawaii, and the island territories. The NED is derived from diverse source data sets that are processed to a specification with a consistent resolution, coordinate system, elevation units, and horizontal and vertical datums. The NED is the logical result of the maturation of the long-standing USGS elevation program, which for many years concentrated on production of map quadrangle-based digital elevation models (DEM). The NED serves as the elevation layer of the *The National Map* (Kelmelis *et al.*, 2003), and it provides basic elevation information for earth science studies and mapping applications in the United States.

Background, Rationale, and History

The history of USGS DEM production is detailed in Osborn *et al.* (2001). The production of 7.5-minute quadrangle-based DEMs began in the mid-1970s, and once-over coverage of the conterminous United States at a post spacing of 30 meters or better was completed in 1999. Production of 10-meter resolution DEMs continues today where the USGS and its partners have the requirement of upgrading the basic 30-meter resolution elevation data coverage. The geospatial data community has made extensive use of these quadrangle-based DEMs; however, a significant amount of pre-processing is required to assemble multiple DEMs into a seamless data set suitable for application. Gesch *et al.* (2002) describe the steps required for production of an elevation layer, including projection transformation and resampling, datum conversions, mosaicking, edge-matching, sliver filling, filtering for artifact removal, and elevation unit conversion. The consistent, seamless structure of the NED removes the requirement for users to handle and individually process multiple input files. Instead, the NED provides application-ready data and allows users to focus on analysis rather than data preparation.

The NED is designed to address the requirement for large-area coverage of the "best available" elevation data. This approach fulfills the *framework* data concept as promoted by the National Spatial Data Infrastructure (NSDI) (Federal Geographic Data Committee, 1995) in which the most commonly needed geographic data themes are integrated into coherent data sets based upon source data from multiple public and private entities. The USGS has been designated as the agency having the lead responsibility for national elevation data (Office of Management and Budget, 2002). As such, the USGS has assembled the NED as an implementation of the framework data concept.

The USGS began the development of seamless elevation data sets in the early 1990s, first working on continental and global data sets at a resolution of 1 kilometer (Gesch *et al.*, 1999). The experience gained in assembling multi-source, multi-resolution elevation data into a global seamless data set proved to be valuable, as the methods were adapted, refined, and further developed for use in producing regional U.S. elevation framework prototypes in 1996. The first

complete seamless coverage of the conterminous United States was finished in 1997 and was based on 10-meter, 30-meter, 2-arc-second, and 3-arc-second resolution DEM source data. In 1999, for the first time, the NED was assembled completely (for the conterminous United States) from 7.5-minute DEM source data (10-meter and 30-meter data). The bimonthly update cycle for the NED began in June 2000 and continues to the present.

SPECIFICATIONS AND PRODUCTION

To maintain seamlessness in its national coverage, the NED uses a raster data model cast in a geographic coordinate system (horizontal locations are referenced in decimal degrees of latitude and longitude). The NED employs a multi-resolution structure, with national coverage at a grid spacing of 1-arc-second (approximately 30 meters). The exception is Alaska where lower resolution source data warrant the use of a 2-arc-second spacing. Where higher resolution source data exist, the NED also contains a layer at a post spacing of 1/3-arc-second (approximately 10 meters). Some areas are also available at a 1/9-arc-second (approximately 3 meters) post spacing, where very high-resolution source data exist. The NED production approach ensures that georeferencing of the layers results in properly nested and coincident data across the three resolutions. In the context of the raster data model used for the NED, the area represented by one elevation post in the 1-arc-second layer is represented by nine elevation posts in the 1/3-arc-second layer, and by eighty-one elevation posts in the 1/9-arc-second layer (Figure 4.1). Where all three resolution layers can be produced, each layer is constructed independently from the same high-resolution source data using an aggregation method appropriate to the grid spacing being produced.

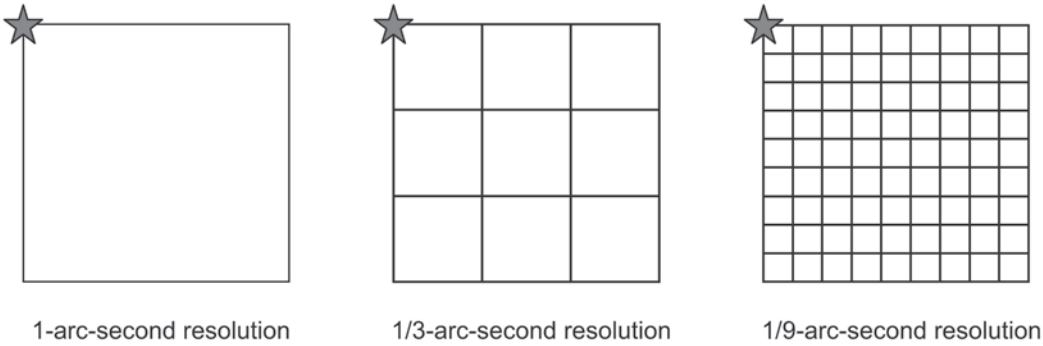

Figure 4.1 NED nested multi-resolution raster elevation layers. The area represented by one elevation post (or cell) in the 1-arc-second layer is represented by nine elevation posts in the 1/3-arc-second layer and by eighty-one elevation posts in the 1/9-arc-second layer.

In all three NED resolution layers, the elevation units are standardized to decimal meters. The horizontal datum for the NED is the North American Datum of 1983 (NAD 83), and the vertical datum is the North American Vertical Datum of 1988 (NAVD 88). Federal Geographic Data Committee (FGDC) compliant metadata are provided for efficient documentation. Additionally, spatially referenced metadata are supplied as an attributed geospatial data layer that captures all metadata from the source DEMs and NED processing steps on a polygonal footprint basis (Figure 4.2).

The NED is a logically seamless data set, as computer-processing considerations require that the data be assembled on a tiled basis, and the tiles collectively form the virtual national mosaic. Currently, NED production uses a 1- by 1-degree tile as the unit for assembly and processing of the 1-arc-second and 1/3-arc-second layers. Adjacent tiles are edge matched to ensure the seamless nature of the data set. In its entirety, the NED comprises nearly 1,400 1- by 1-degree tiles, with more than 900 tiles covering the conterminous United States, more than 400 covering Alaska, and the remainder covering Hawaii and the island territories.

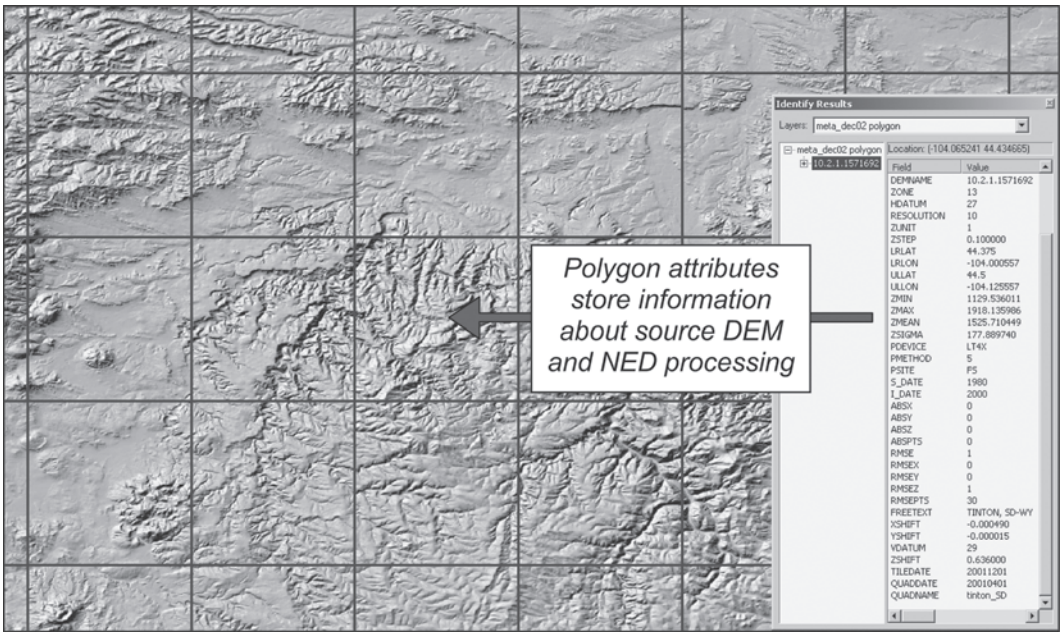

Figure 4.2 NED spatially referenced metadata layer. See color plate in Appendix C.

When a NED tile is assembled, the best available source data are selected according to the following criteria (ordered from first to last): high-resolution elevation data (usually derived from lidar or aerial photogrammetry), USGS 10-meter DEM, USGS 30-meter Level 2 DEM, USGS 30-meter Level 1 DEM, and USGS 2-arc-second DEM (see Osborn *et al.*, 2001 for an explanation of DEM level designations). The goal is to continuously upgrade the NED, thus the emphasis on high-resolution lidar and photogrammetric source data, and 10-meter DEMs, as the primary and secondary sources, respectively. For the conterminous United States, the area covered by high-resolution elevation data and 10-m DEMs is increasing continuously, so the percentage of the 1-arc-second NED layer derived from 30-meter DEMs has been decreasing correspondingly. Figure 4.3 shows the composition of the NED source data by DEM type for the first five-and-a-half years of NED bimonthly updates. As of January 2006, more than 60 percent of the conterminous United States had been covered by source data with a resolution of 10 meters or better. Figure 4.4 shows the geographic distribution of source data resolution across the conterminous United States.

The NED is assembled from approximately 59,000 files of source elevation data. As source data for NED production, more than 55,000 DEM files are used for the conterminous United States and nearly 4,000 DEM files for Alaska, Hawaii, and the island territories. Production of 7.5-minute DEMs at the 10-meter (or 1/3-arc-second) post spacing is an ongoing activity at the USGS, so the NED is updated on a regular basis to incorporate all new USGS DEM production, thus retaining the "best available data" framework concept. A new version of the NED is released every two months, containing updated areas for which new source DEMs became available since the previous release. The new source data may come from USGS production or from newly available high-resolution data acquisitions. On average, approximately 8 percent of the total number of 1- by 1-degree tiles are updated at each release. An update is required for a tile if even one new DEM file is available, as edge matching must be done to ensure the seamless quality of the NED. The spatially referenced metadata provided with each NED release indicate the specific areas where new source DEMs have been incorporated since the previous release.

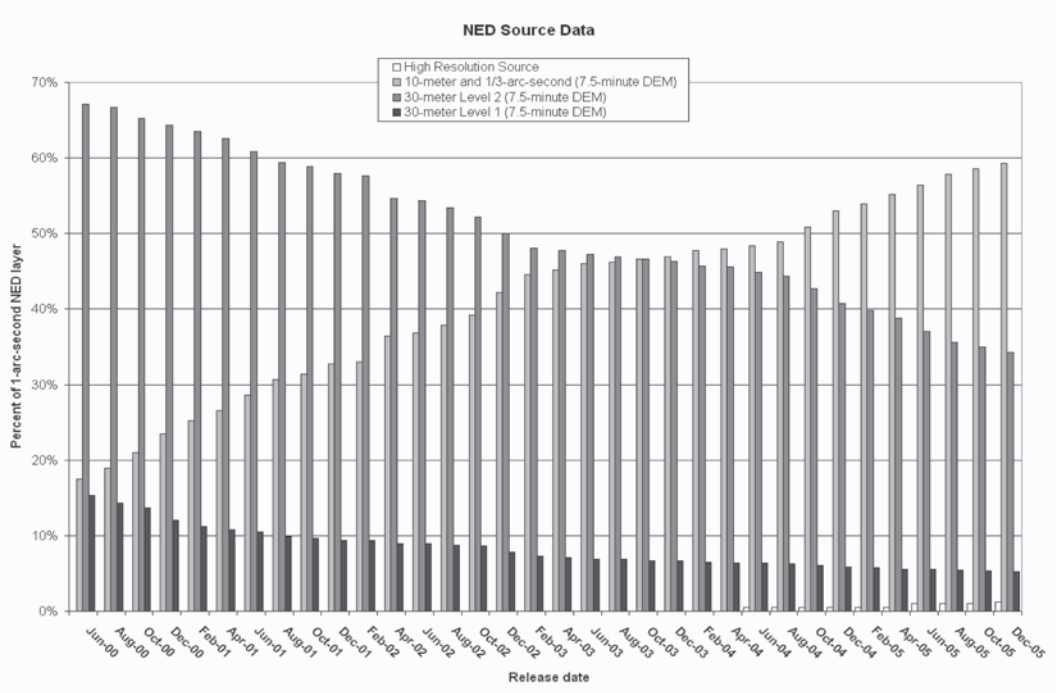

Figure 4.3 Source data by DEM type for each NED release.

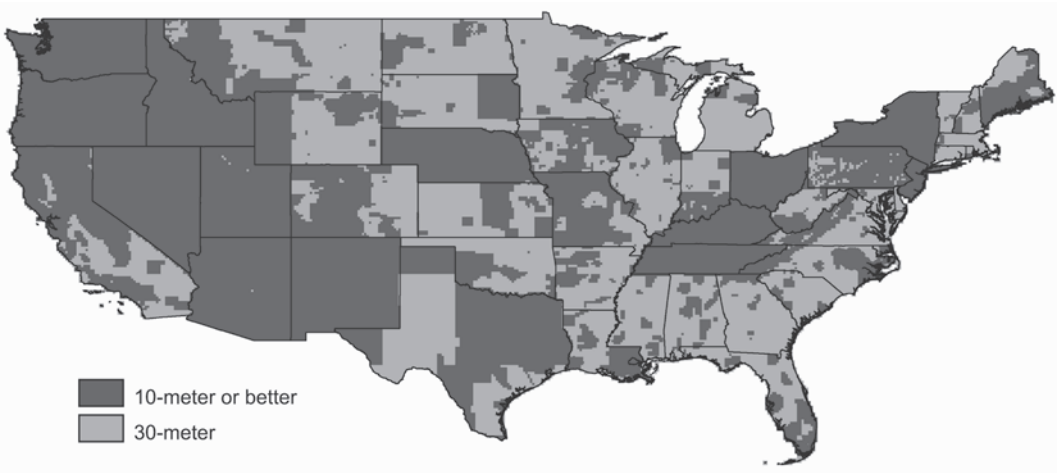

Figure 4.4 Geographic distribution of NED source data resolution (as of January 2006).

NED Production Steps

NED assembly and updating are accomplished with a highly automated production process that was developed specifically for this seamless elevation data set. The main steps in the process are outlined in Figure 4.5. The selection of source data is accomplished by an automated query of a database of USGS and partner-supplied DEMs. The "best available" data criteria outlined above are applied to select specific file-based DEMs from the database. The headers of the selected DEMs are read to create an index, which controls production and triggers subsequent processing steps. Industry standard tools from the National Geodetic Survey (NGS), NADCON and VERTCON, are used to perform horizontal and vertical datum transformations, respectively.

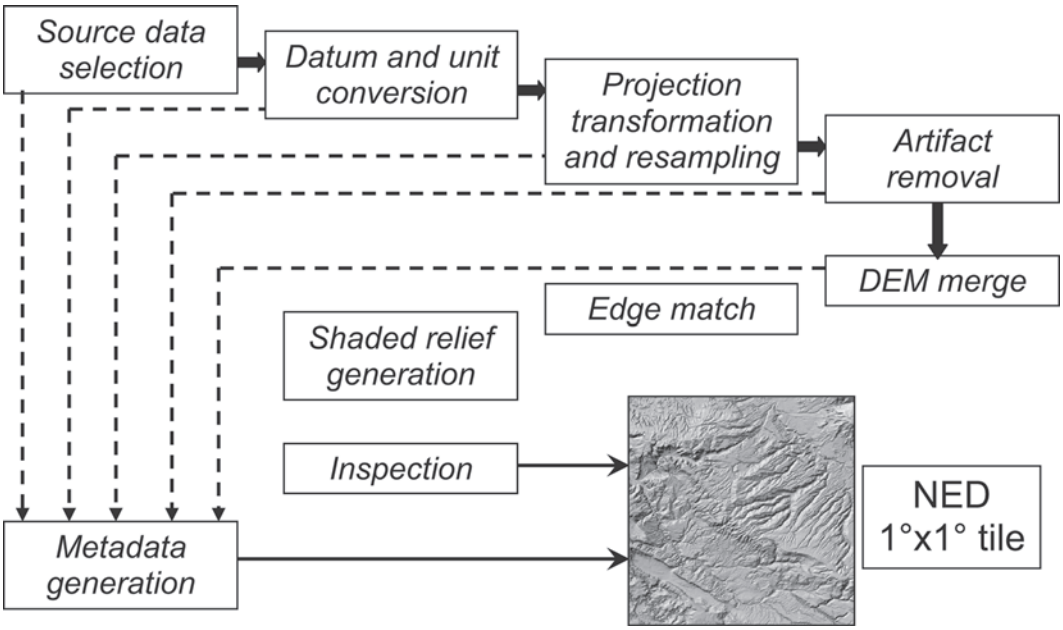

Figure 4.5 The NED production process.

The source DEMs are projected from their native coordinate system to a geographic coordinate system (decimal degrees of latitude and longitude) using standard cartographic transformation software. Resampling of the original elevation values is done with an implementation of cubic convolution that is optimized for elevation data by maintaining the integrity of shorelines and water bodies. Artifact removal is performed on the older USGS Level 1 DEMs that were produced with photogrammetric methods. The "mean profile filter" (Oimoen, 2000) was specifically designed to process these 7.5-minute DEMs. The filter process uses a series of directional filters to isolate the high-frequency artifacts, which are then subtracted from the DEM. The magnitude of these artifacts is small, typically less than 1 meter, so the change to the DEM is negligible, but the removal results in significant improvements in derivative elevation products, such as shaded relief, slope, and aspect.

The final steps in the production process include paneling the DEMs to fill the 1- by 1-degree tile, filling slivers of missing data along DEM boundaries as necessary by interpolating adjacent values, and edge matching the seams along the DEM boundaries and tile edges. The edge match algorithm uses a feathering approach that maintains local slope continuity across the seam. Figure 4.6 shows the results of the artifact filtering, sliver filling, and edge matching operations for an area derived from USGS Level 1 DEMs. Finally, a shaded-relief image of the tile is generated for inspection by an analyst to verify successful processing, especially artifact filtering and edge matching. In some cases, DEM header information, which automatically triggers certain processing options, is incorrect, and the result is data that are not acceptable for inclusion into the NED. These cases are detected in the visual inspection step, the DEM header is corrected, and the tile is submitted for reprocessing. Tiles passing inspection are transferred to the next release version, and the spatially referenced metadata are updated accordingly.

An interactive map server (Figure 4.7) on the NED home page (http://ned.usgs.gov/) allows a user to display the NED data source index, which indicates the date of the most recent update, the resolution of the source data, and the production method of the source data for specific areas. The user can also query the spatially referenced metadata to examine additional information about each file-based DEM used to assemble the NED. The NED Web site also contains documentation on the NED assembly process, accuracy, metadata, standards, data distribution, and release notes.

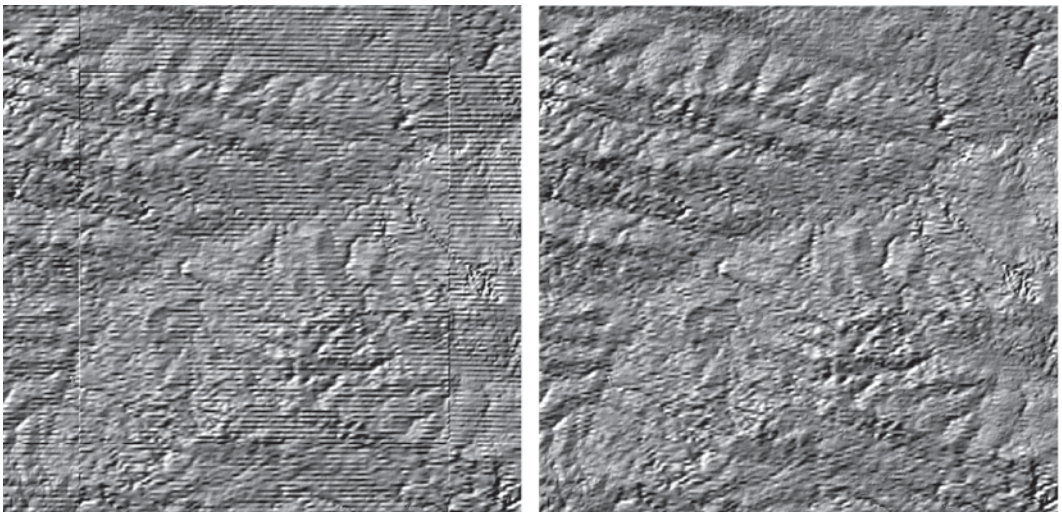

Figure 4.6 Source DEMs without artifact filtering, sliver filling, and edge matching are shown on the left. NED data produced with artifact filtering, sliver filling, and edge matching operations are shown on the right.

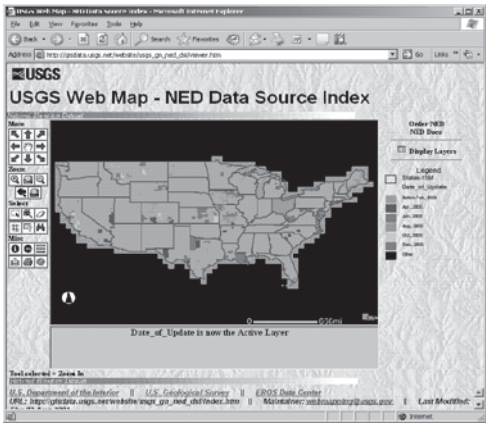

Figure 4.7 Data source index, available on the NED home page (http://ned.usgs.gov/), displays the most recently updated areas in the NED. See color plate in Appendix C.

Data Distribution

In keeping with the framework concept of easily accessible data, NED products are available in several common formats through a Web-based seamless data distribution system (http://seamless.usgs.gov/) linked to the NED home page. The system uses interactive map server technology to provide users the capability for viewing shaded relief images derived from the NED. The map server also includes numerous reference layers to help users define their study areas. The system incorporates a geographic names capability whereby users can automatically pan and zoom to specific feature locations. Orders for products resulting in network-compatible file sizes can be downloaded interactively at no cost to the user. Products covering very large areas, including the entire data set, are available on hard media (Figure 4.8).

ACCURACY ASSESSMENT

The accuracy of the NED varies spatially because of the variable quality of the source DEMs. As such, the NED inherits the accuracy of the source DEMs. Some accuracy statistics are available in the header records of the USGS DEM source files, and this information is captured in the spatially

referenced metadata. Many times, this accuracy information has limited usefulness because it is a relative measure of how well the DEM fits the source material from which it was generated. In an effort to provide more information to users on the vertical accuracy of the NED, the data set has been tested by comparing it with an independent reference source of very high accuracy. The reference data are the geodetic control points that NGS uses for gravity and geoid modeling (Smith and Roman, 2001; National Geodetic Survey, 2003). The distribution of this set of more than 13,000 high-precision survey points across the conterminous United States is shown in Figure 4.9.

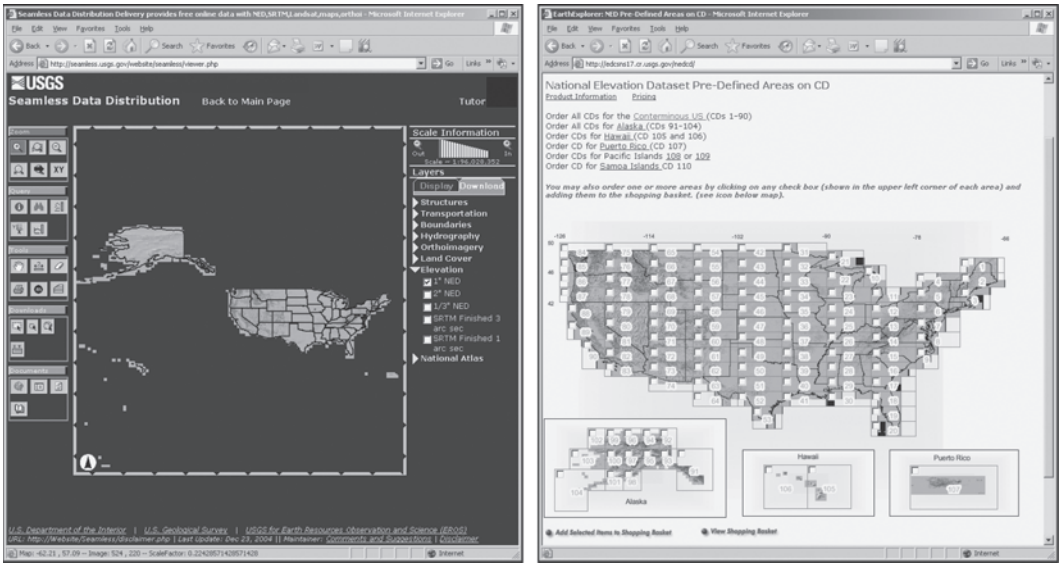

Figure 4.8 Web-based seamless data distribution system (http://seamless.usgs.gov/) for viewing and downloading of NED products (left). Large area coverage of NED products available on hard media (right). See color plate in Appendix C.

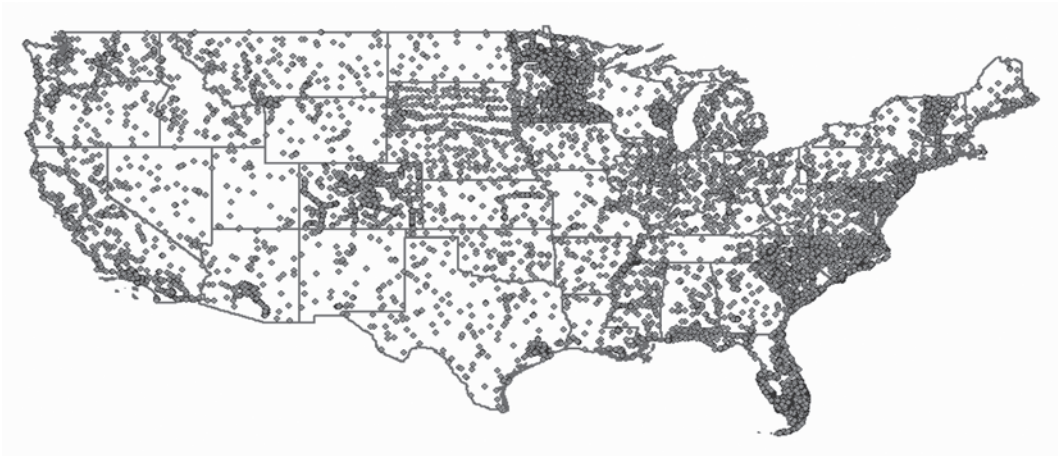

Figure 4.9 Reference control point data set used for accuracy assessment of the NED. See color plate in Appendix C.

Absolute Vertical Accuracy

To complete the accuracy assessment, the NED value at each of the NGS control point locations was derived through bilinear interpolation, and error statistics were calculated (Table 4.1). The overall absolute vertical accuracy expressed as the root mean square error (RMSE) is 2.44 meters. Table 4.1 also contains the accuracy expressed in terms of the National Map Accuracy Standards (NMAS), which use a 90 percent confidence interval, and in terms of the National Standard for Spatial Data Accuracy (NSSDA), which uses a 95 percent confidence interval. The methods described in Maune *et al.* (2001) were used to convert the measured vertical RMSE to equivalent NMAS and NSSDA expressions.

Table 4.1 Error statistics (in meters) of the NED vs. 13,305 reference geodetic control points.

Minimum	Maximum	Mean	Standard Deviation	RMSE	NMAS (90%)	NSSDA (95%)
–42.64	18.74	–0.32	2.42	2.44	3.99	4.75

An advantage of the 2.44-meter RMSE as an accuracy report is that it is an actual measured quantity, in contrast to the often quoted RMSE of 7 meters for USGS DEMs, from which most of NED is derived. The 7-meter RMSE, often cited as the accuracy of USGS 7.5-minute DEMs, is a production goal described in the USGS Data Users Guide 5—Digital Elevation Models, last published in 1993 and traditionally known by many users as the "blue book" (see also U.S. Geological Survey, 1997). Note that the version of the NED that was tested by comparison with the Global Positioning System (GPS) points was the 1-arc-second layer released in June 2003, which was the last version assembled completely from USGS 10-meter and 30-meter 7.5-minute DEMs. Since that time, some areas have been updated based on high-resolution lidar or photogrammetric data, which may have even better accuracy than the quadrangle-based USGS DEMs.

Accuracy assessments were conducted on earlier versions of the NED using a smaller set of control points from the NGS known as the High Accuracy Reference Network (HARN). Approximately 5,800 points were used to measure the absolute vertical accuracy of the 1-arc-second layer of the NED for the conterminous United States as it existed in September 1999, October 2001, and October 2002. Table 4.2 shows the improvement in overall vertical accuracy of the NED, as the more recent versions have incorporated better source data. Most of the HARN points used for the earlier assessments were also included in the larger GPS benchmarks data set, which was used for the most recent assessment of the June 2003 version of the NED.

Table 4.2 Results of accuracy assessments of the NED vs. reference geodetic control points (all numbers are in meters).

Version Date of the NED	RMSE	NMAS (90%)	NSSDA (95%)
September 1999	3.74	6.15	7.34
October 2001	3.13	5.15	6.14
October 2002	2.70	4.44	5.29
June 2003	2.44	3.99	4.75

Use of the NED spatially referenced metadata also allows for the calculation of accuracy statistics segmented by source DEM characteristics. Because the NED is derived from source DEMs that were produced with several different methods, it may be important for a user to know what levels of accuracy can be expected for areas based on DEMs produced with the various methods. The four primary production methods used for USGS 7.5-minute DEMs include electronic image correlation (Gestalt Photo Mapper (GPM) instrument), manual profiling (MP) on stereoplotters, contour-to-grid interpolation (CTOG), and an improved contour-to-grid interpolation known as "LineTrace+" (LT4X). Details for each production method are given in Osborn *et al.* (2001). To calculate the accuracy of DEMs resulting from each production method, the reference control point data set was partitioned into subsets according to the production method of the

quadrangle on which each point was located. Table 4.3 shows the error statistics for the areas of the NED derived from DEMs produced with each of the four production methods. Note that the DEMs derived from photogrammetric methods (GPM and MP) are less accurate than those derived from 1:24,000-scale contours. This is not surprising, given that the photogrammetric DEMs were compiled from 1:80,000-scale aerial photography and were a by-product of the orthophoto generation process.

Table 4.3 Error statistics (in meters) of the NED for areas derived from USGS 7.5-minute DEMs produced with each of the four primary production methods.

Production Method	Number of Reference GPS Points	Minimum	Maximum	Mean	Standard Deviation	RMSE
GPM	809	–11.98	17.44	2.00	4.21	4.66
MP	465	–15.31	14.34	0.05	3.63	3.63
CTOG	1,537	–20.83	9.18	–0.60	1.94	2.03
LT4X	10,476	–42.64	18.74	–0.47	2.12	2.17

Land surface characteristics derived directly from the NED, including slope, aspect, and local relief, allow for examining accuracy as a function of specific terrain conditions. Figure 4.10 shows the NED error at each GPS control point plotted against elevation, slope, aspect, and local relief (relief within approximately one square mile centered on the point location). The NED errors appear to be truly random, as there is no discernible correlation or relationship with any of the terrain parameters. This is evident in the distribution of data points in the scatterplots; in each case, the values are uniformly distributed around the zero error axis. Thus, in general, NED users can expect a consistent level of accuracy across the data set regardless of varying terrain conditions.

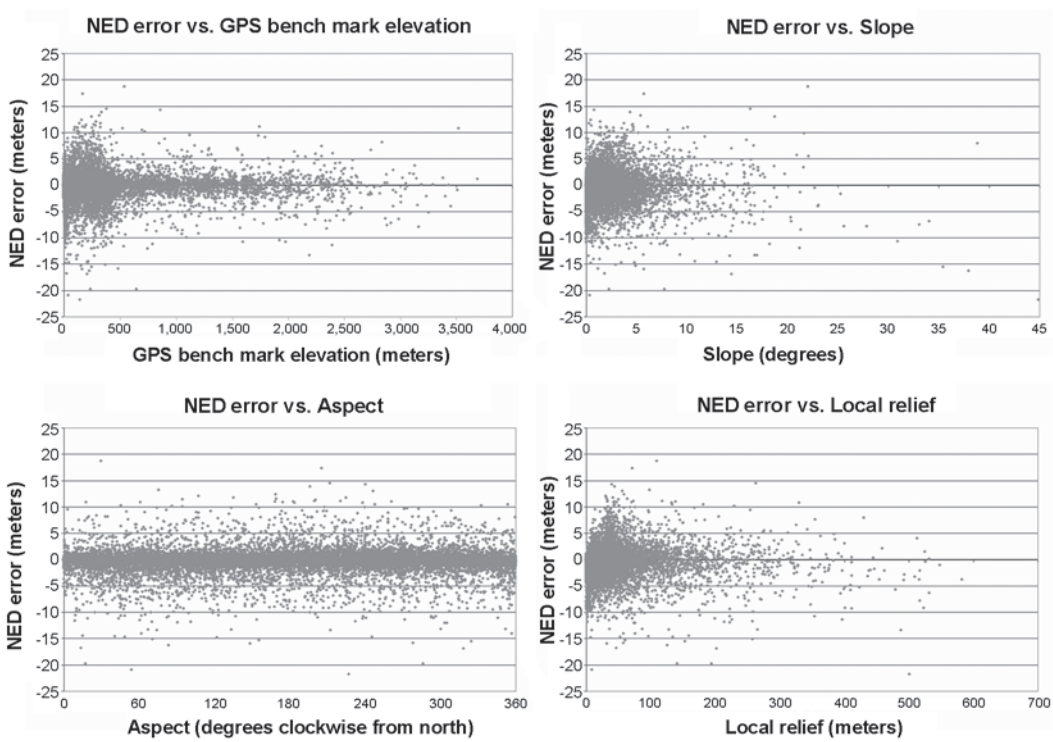

Figure 4.10 NED errors (in meters) plotted against elevation (upper left), slope (upper right), aspect (lower left), and local relief (lower right).

Relative Vertical Accuracy

For some applications of elevation data, the relative, or point-to-point, vertical accuracy is more important than the absolute vertical accuracy. Whereas absolute accuracy accounts for the combined effects of systematic and random errors, relative accuracy is a measure of just random errors. The relative vertical accuracy of a data set is especially important for derivative products that make use of the local differences among adjacent elevation values, such as slope and aspect calculations. To characterize the relative vertical accuracy of the NED, the same set of reference geodetic control points used in the assessment of absolute vertical accuracy was processed and analyzed. As with the test of absolute accuracy, the NED 1-arc-second layer released in June 2003 was tested. Each point in the reference control point data set was processed to identify its closest neighboring point, and this resulted in 9,187 unique point pairs for which the NED elevation at each point location and the distance between the points were recorded. The relative vertical accuracy, *RV*, was calculated for each point pair with the following formula (National Digital Elevation Program, 2004):

$$RV = |\Delta ref - \Delta NED|$$

where Δref = |reference elevation difference|
ΔNED =|NED elevation difference|

Averaged over all 9,187 point pairs, the relative vertical accuracy is 1.64 meters (other summary statistics are shown in Table 4.4). The separation distance for points in a pair ranges from a few meters to more than 118 kilometers, with the average distance slightly greater than 7,000 meters and the median distance slightly less than 2,200 meters. Assessing relative accuracy across very long distances can have the effect of averaging random errors, thereby reducing the overall error. As stated, the pairs of reference points used here have a wide range of distances. At the lower end of the range is a subset of 109 point pairs that have a distance of 90 meters or less, which is about three times the nominal post spacing of the 1-arc-second NED layer. For this subset of 109 point pairs, the average relative vertical accuracy is 0.78 meters, so the very closely spaced points that were tested show a very high degree of relative accuracy.

Table 4.4 Relative vertical accuracy statistics for the NED based on 9,187 unique pairs of reference geodetic points (all numbers are in meters).

Minimum	Maximum	Mean	Standard Deviation	Median
0.00	22.07	1.64	2.08	0.89

One use of relative accuracy information is to estimate the uncertainty of slope calculated from raster elevation data such as the NED. Slope is often calculated from DEMs by assigning a slope value to each grid cell based on the maximum elevation change across its eight adjacent neighbors (a 3-by-3 window). To illustrate how relative vertical accuracy of a DEM affects slope accuracy, assume that an area of the land surface represented by a 3-by-3 window of elevation cells is flat. Thus, all nine elevation values should be the same and the derived slope should be zero. However, because of random errors inherent in elevation data, assume that the maximum elevation difference among the cells surrounding the center cell of the window is 1.64 meters. The minimum measurement baseline for slope within the window occurs when the maximum elevation difference is between two cells that are either immediately above and below, or left and right, of the center cell. In this case, if the post spacing of the DEM is 30 meters, the measurement baseline, or run, for slope calculation is 60 meters. Given the elevation difference (rise) of 1.64

meters and the baseline (run) of 60 meters, the calculated slope (rise/run x 100) is 2.73 percent (1.57 degrees). Thus, using the relative vertical accuracy figure of 1.64 meters results in an average accuracy of 2.73 percent for slope derived from the 1-arc-second NED layer. Figure 4.11 depicts in graphic form how this estimate of slope accuracy is calculated.

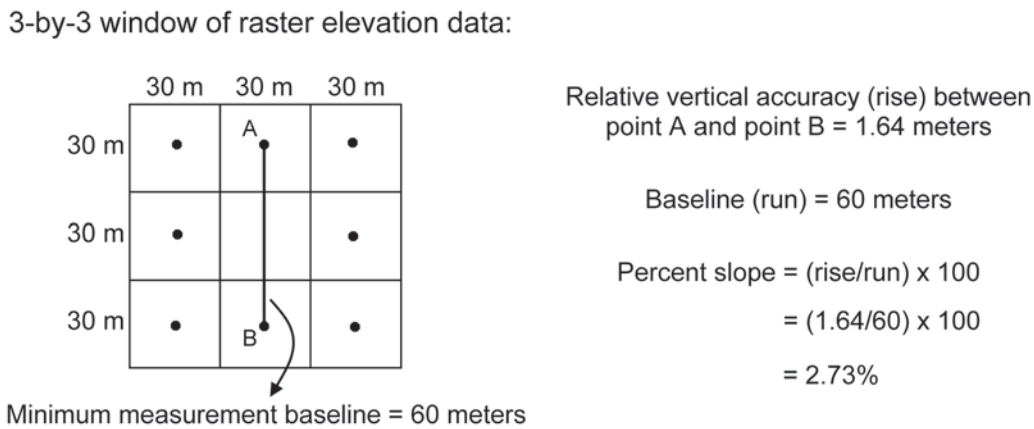

Figure 4.11 Calculation of accuracy of slope derived from 30-meter resolution elevation data. Assume that the area covered by the window is flat, and thus all elevation posts within the window should be the same. However, random error in the elevation data causes a difference of 1.64 meters in elevation between point A and point B. If the elevation data were free of error, a slope of zero would be assigned to the center cell, but in this case a slope of 2.73% is calculated, and it represents the slope accuracy.

One caveat to note about the accuracy assessment presented here is that even though the reference control point data set is large, the number of quadrangle-based USGS DEMs on which the points are located is relatively small. Approximately 11 percent of the source DEMs have at least one point located within. Thus, if users have a need for very specific accuracy information for the NED for a local area, a separate assessment should be done with suitable reference data just for that area. In addition, even though the reference control points are located broadly across the conterminous United States, the distribution of elevations and terrain conditions within the data set is not completely representative of the nation's topography. This stands to reason, as surveyed benchmarks are generally located in open, accessible areas. Thus, high elevation, steep slope locations are under-represented in the reference data set. Despite this limitation with the reference data, the overall vertical accuracy reported here is useful for applications that need to factor in the quality of the NED over large areas. Also, prior to the accuracy assessment reported here, there were no actual measured absolute or relative error statistics for USGS DEMs as a whole, so for the first time the user community now has a useful quantitative estimate of quality. As the NED is continually upgraded based on new acquisitions of high-resolution data, the overall vertical accuracy should improve. In many cases, the source data sets will have comprehensive error reports supplied with them, and these statistics will be captured and preserved in the NED metadata.

APPLICATIONS

As a primary source of basic topographic information for the United States, the NED is used in numerous applications that require elevation as an input. Elevation data are critically important for many hydrologic studies, and these studies are one of the main uses of the NED and associated derived products. The USGS data set known as the Elevation Derivatives for National Applications (EDNA) is based on the 1-arc-second NED and offers a multi-layered hydrologically conditioned database that was developed specifically for large-area hydrologic modeling applica-

tions (Verdin, 2000; Franken, 2004). Hydrologic conditioning results in elevation data with improved hydrologic flow representation and allows for derivation of multiple raster and vector layers optimized for hydrologic modeling, including flow direction, flow accumulation, streamlines, catchments, slope, and aspect. A primary use of the EDNA layers has been for drainage basin delineation and characterization (Kost and Kelly, 2001). Interactive basin delineation based on the EDNA data set is available through Web-enabled tools linked to the EDNA Web site (Verdin *et al.*, 2004) (Figure 4.12). These tools allow for delineation of the watershed above any point on the landscape, not just at stream junctions or other pre-defined points. Watershed characteristics, including the calculated mean annual stream flow at the basin outlet point, can be displayed, and the watershed delineation can be downloaded. The EDNA database has also been used for flash flood modeling and prediction (Arthur *et al.*, 2005), national assessment of hydroelectric power potential (Carroll *et al.*, 2004; Hall *et al.*, 2004), and watershed-based sampling design for water quality monitoring sites (Detenbeck *et al.*, 2005). Current EDNA development includes taking advantage of the higher resolution layers of the NED for improved flow routing.

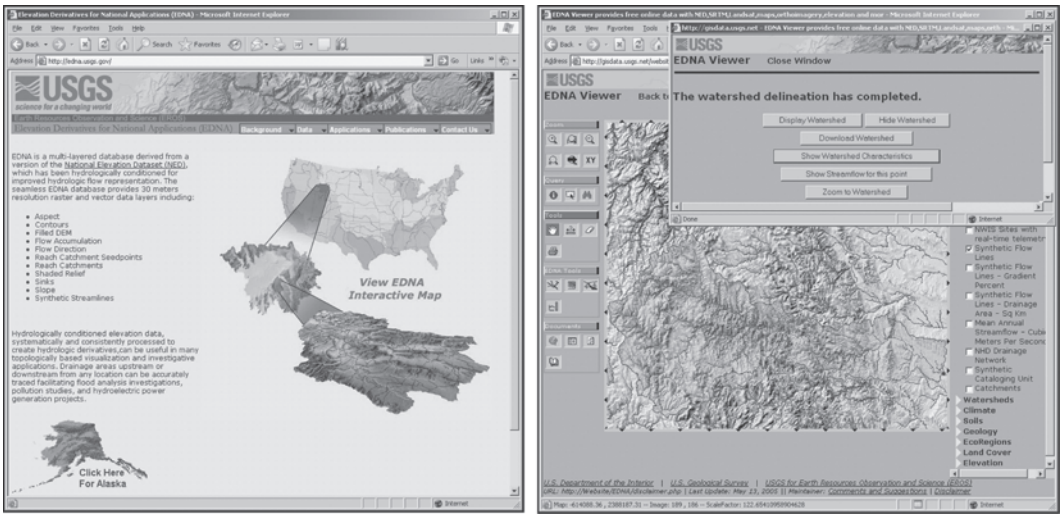

Figure 4.12 EDNA Web site (http://edna.usgs.gov/), on the left, and the Web-based interactive drainage basin delineation tool available on the EDNA data viewer, on the right. See color plate in Appendix C.

Data from the NED have been merged with bathymetry data to facilitate applications at the land/water interface. Many applications of geospatial data in coastal environments require knowledge of the near-shore topography and bathymetry. However, because existing topographic and bathymetric data have been collected independently for different purposes, it has been difficult to use them together. A tool developed by the National Oceanic and Atmospheric Administration (NOAA), VDatum (Parker *et al.*, 2003; Myers, 2005), is used to transform disparate data sets into a common vertical datum, which then facilitates development of merged seamless elevation models across the land/water interface. The USGS and NOAA are working collaboratively to produce such merged coastal topographic/bathymetric data sets (Gesch and Wilson, 2002). Figure 4.13 shows a merged elevation model for Tampa Bay, Florida, in which the topographic data came from the 1-arc-second NED layer and the bathymetric data came from NOAA's hydrographic survey database. This hybrid model has been used for improved storm surge simulations for Tampa Bay (Weisberg and Zheng, 2005). As the quality of the NED 1/3-arc-second and 1/9-arc-second layers improves through integration of recent, high-resolution data acquisitions, the quality of merged topographic/bathymetric elevation models made from those layers will improve accordingly.

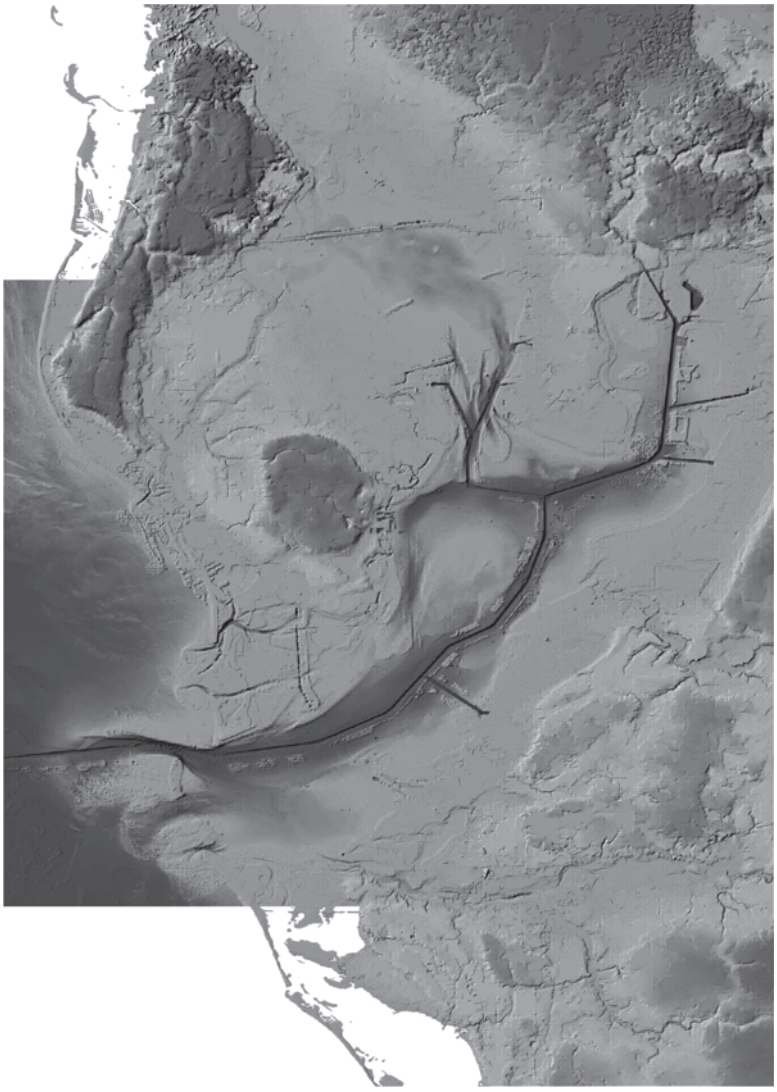

Figure 4.13 Merged elevation model for Tampa Bay, Florida. The topographic data came from the 1-arc-second NED layer and the bathymetric data came from NOAA's hydrographic survey database. See color plate in Appendix C.

Because topographic information is a fundamental requirement for so many earth science studies and operational geospatial applications, the NED has gained wide acceptance and attained broad usage by the user community. Among the characteristics of the NED that support its broad applicability are its national coverage, multi-resolution design, and regular update cycle. Some of the applications that have benefited from these advantages are large-area land cover mapping (Homer *et al.*, 2004), regional soil erosion vulnerability modeling (Das *et al.*, 2004), climate data analysis (Gallo, 2005), vegetation height estimation (Kellndorfer *et al.*, 2004), and wildland fire fuel mapping (see http://www.landfire.gov/). Current applications research at the USGS includes use of the NED as the historical component for topographic change detection and monitoring across the United States and development of a Web-based tool for generation of contours from the NED for use in producing updated topographic map products.

CURRENT DEVELOPMENT AND FUTURE DIRECTIONS

From the beginning of development of the NED and continuing to the present, the goal has always been to provide the best publicly available elevation data for the nation. Many sources of elevation data are available that could potentially be used for the NED; however, the focus has been, and will continue to be, on integrating the highest resolution, highest accuracy data that are free from licensing or other redistribution restrictions. The NED is a public domain resource, and it must remain so to fulfill the requirements of being a national framework geospatial data theme. To make sure that the NED fully meets the intent of the NSDI framework approach, the USGS elevation program is taking the direction that the primary source for updating the NED is recent collections of high-resolution data acquired through partnerships with other organizations. When necessary, the USGS still produces DEM data from quadrangle-based hypsography data, but only when there is no clear alternative for data to upgrade the NED.

In contrast to the situation several decades ago, there are many elevation data producers in addition to the USGS. Numerous federal, state, local, and tribal agencies either produce or contract for elevation data. Much of the data are actually generated by private sector mapping and engineering companies. For the NED to truly reflect the best publicly available data, elevation data from all these entities must be considered as potential information sources. The USGS has a cadre of liaisons to states and federal agencies that are dedicated to developing and implementing partnerships that benefit both parties by improving USGS geospatial data production, integration, and distribution. Much of the newer, high-resolution elevation data that have been integrated into the NED are the result of partnering arrangements led by the liaison staff.

Another entity that fosters collaboration on elevation data development is the National Digital Elevation Program (NDEP), which is a consortium of federal agencies working together to satisfy multiple elevation data requirements. The states also have a voice in the NDEP through a representative from the National States Geographic Information Council. Details on the background and operations of the NDEP are given in Osborn *et al.* (2001). The NDEP has produced a best practices document titled "Guidelines for Digital Elevation Data" (National Digital Elevation Program, 2004) to help member agencies as they acquire high-resolution elevation data. Data collected with the characteristics discussed in the guidelines meet the requirements of multiple federal agencies, and thus make efficient use of federal funds available for new geospatial data collection. The NDEP also operates a project tracking system whereby information on proposed, planned, in-work, or completed elevation projects is posted and shared (Figure 4.14). The project tracking tool is useful for agencies that are seeking partners to acquire data over a specific area. The NED benefits from NDEP activities in that it becomes the repository for bare earth elevation data as projects are completed. In this way, the benefits of data acquired by one agency are extended to other agencies, and eventually to the general user community, through the NED.

A new USGS activity, the Center for Lidar Information Coordination and Knowledge (CLICK), is another forum for information exchange and topographic data discovery that benefits the NED. CLICK is a virtual Web-based center (Figure 4.15) with the goal of providing a clearinghouse for lidar information and point cloud data. The CLICK Web site (http://lidar.cr.usgs.gov) provides a bulletin board with numerous topics related to lidar data for discussion among the community, including topics on bare earth data and NDEP. The site also includes a tool for viewing the coverage of available data and downloading point cloud data, in addition to an extensive list of lidar-related Web sites and references. Data acquired for distribution through the CLICK are also used as a source of high-resolution bare earth elevation data to enhance the coverage of the NED 1/9-arc-second layer. In addition, through the CLICK, users have access to the full-return point cloud form of lidar data that is included in the NED as bare earth gridded elevation data.

The NED will continue to be upgraded as new high-resolution source data become available. Ideally, source data that support the 1/9-arc-second posting will be acquired and used to update all three NED layers. In most cases, these source data will come from lidar or photogrammetric data, such as mass points and breaklines compiled from very large-scale stereo photography. To

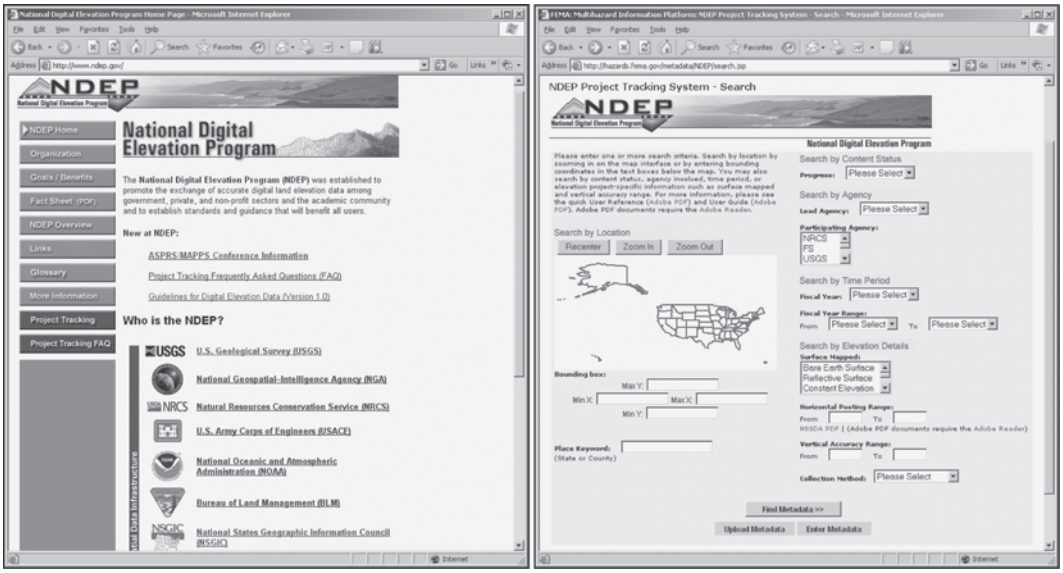

Figure 4.14 The NDEP Web site (http://www.ndep.gov/), shown on the left, includes a link to the NDEP project tracking system, shown on the right. See color plate in Appendix C.

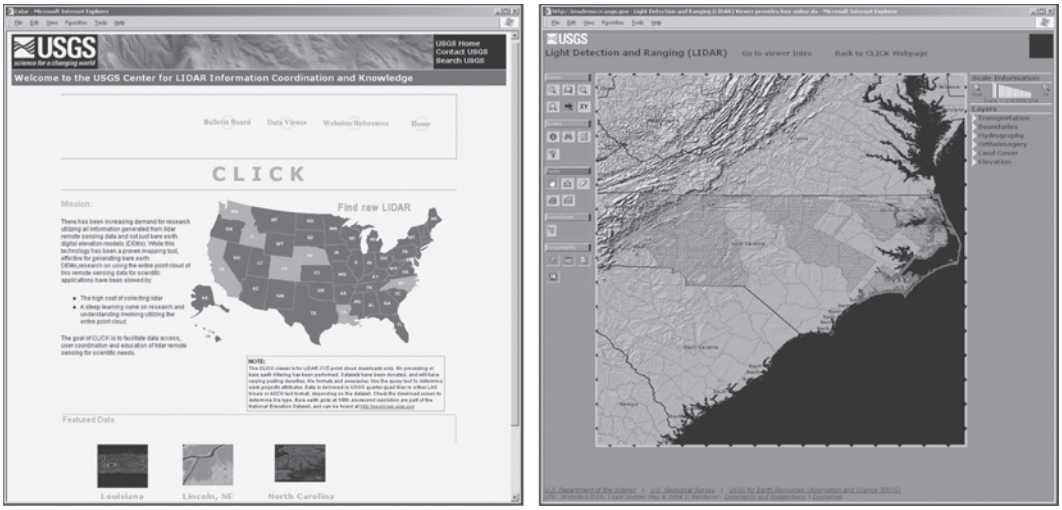

Figure 4.15 The USGS Center for LIDAR Information Coordination and Knowledge (CLICK) is a Web-based (http://lidar.cr.usgs.gov) virtual center that serves as a clearinghouse for lidar information exchange and point cloud data distribution. See color plate in Appendix C.

date, airborne interferometric synthetic aperture radar (IFSAR) data have not been used as a source for the NED, but as bare earth processing algorithms improve, or as coverage over suitable land cover such as Alaskan tundra increases, then these data will become a viable source for updating the NED.

As the primary USGS elevation data product, the NED is at the center of much of the topographic research and development conducted throughout the USGS. Driven by customer requirements and technology considerations, the goal of the USGS elevation program for many years was the production of 7.5-minute DEMs. These DEMs will still be produced for areas where it is unlikely that high-resolution, high-accuracy lidar or photogrammetric data will be available in the near future. In these cases, 10-meter DEMs in the standard Universal Transverse Mercator projection with a fully populated header record will be produced only when a funding partner

requires it. Otherwise, data will be produced in a geographic coordinate system at a posting of 1/3-arc-second, which facilitates direct integration into the NED with minimal processing. Because the NED is the primary elevation data set produced and distributed by the USGS, distribution of the 7.5-minute DEMs was discontinued as of early 2006. By directing all users to the NED instead of supplying the older tiled data, they are assured of receiving the highest quality, most up-to-date elevation layer for the nation.

As more high-resolution, high-accuracy source data become available, it is anticipated that the areal coverage of the NED 1/9-arc-second layer will increase significantly. When new areas are covered by 1/9-arc-second data, the corresponding portions of the 1/3-arc-second and 1-arc-second layers are also upgraded. A current development activity at the USGS involves investigation of approaches to provide raster elevation data with a user-specified resolution, projection, units, and file format. If such a system could be implemented efficiently, then the NED architecture could be modified to hold only properly prepared source data, and distributable products could be generated to customer specifications on the fly. However, for the foreseeable future, the NED will continue to be provided in the three layers of differing resolution, which allows a user to access elevation data at the resolution that best matches the application and other input data layers. The continuing goal for the NED is to provide quality controlled, well documented elevation data that are useful for many geospatial applications.

EXAMPLE DATA

To help geospatial data users explore the use of the multi-resolution NED, examples are provided here as graphics and as digital data sets on the media accompanying this volume. The example areas include portions of the NED derived from different types of source data.

Figure 4.16 shows data from the three NED layers for an area in southern West Virginia. The source data for this area were derived through photogrammetric compilation of mass points and breaklines (MPBL) and subsequent surface generation. Figure 4.17 shows how the integration of the high-resolution photogrammetric data is reflected in the source data polygons in the NED spatially referenced metadata. The NED spatially referenced metadata are included with the elevation data for each example area.

Figure 4.18 shows data from the three NED layers for an area in southern Louisiana. The source data for this area are lidar-derived elevation grids.

Figure 4.19 shows data from two NED layers for an area in western Montana. The source data for this area are USGS 7.5-minute DEMs that were derived from 1:24,000-scale hypsography and hydrography through contour-to-grid interpolation.

AUTHOR BIOGRAPHY

Dean Gesch is employed by the U.S. Geological Survey (USGS) as a research physical scientist at the Center for Earth Resources Observation and Science (EROS) in Sioux Falls, South Dakota. His work is focused on research, development, and applications related to digital topographic data, including the investigation of newer remote sensing sources of elevation data, development of national and global seamless elevation data sets, accuracy assessment, topographic change detection and monitoring, and analysis of the risk of sea level rise based on high-resolution coastal mapping data sets. His previous experience includes work at NASA's Goddard Space Flight Center investigating remote sensing applications and work in terrain analysis at the Defense Mapping Agency. His educational background includes a bachelor's degree in geography from Carroll College, Waukesha, Wisconsin (1982), and a master's degree in geosciences from Murray State University, Murray, Kentucky (1984). He is currently a PhD candidate (ABD) in the geospatial science and engineering program at South Dakota State University, Brookings, South Dakota.

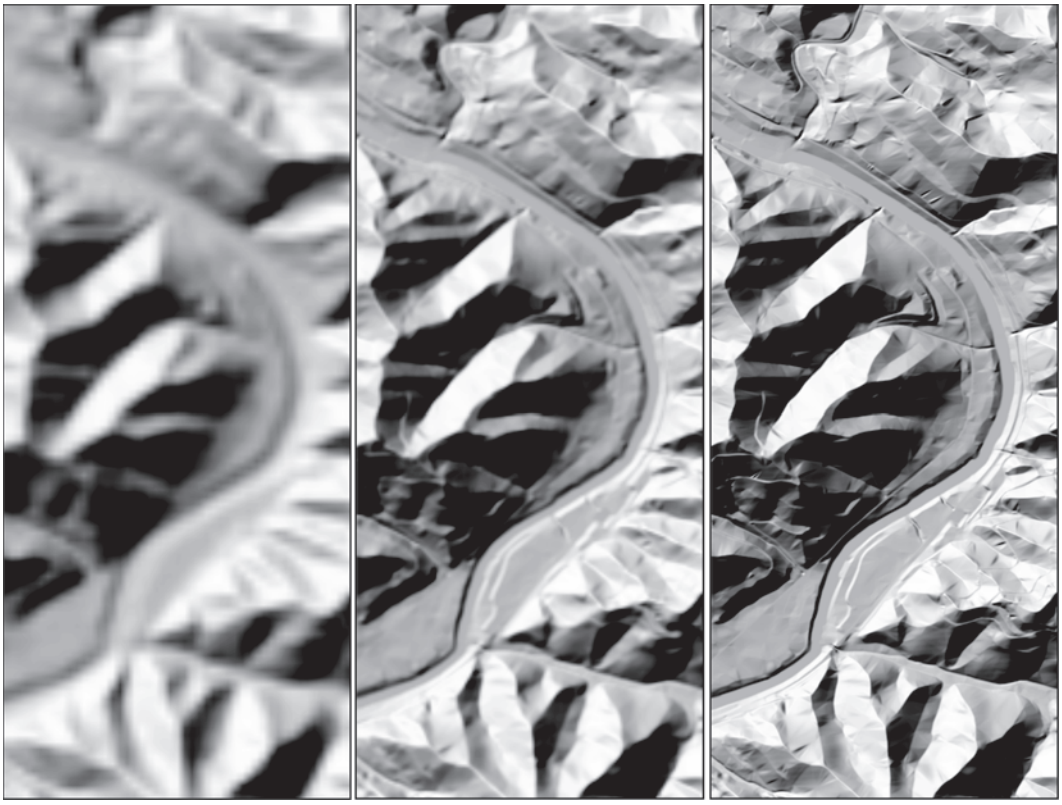

Figure 4.16 Multi-resolution NED layers for an area in West Virginia (1-arc-second data on the left; 1/3-arc-second data in the center; 1/9-arc-second data on the right). These data are derived from photogrametrically compiled mass points and breaklines. The digital data for this example area are provided on the media accompanying this book.

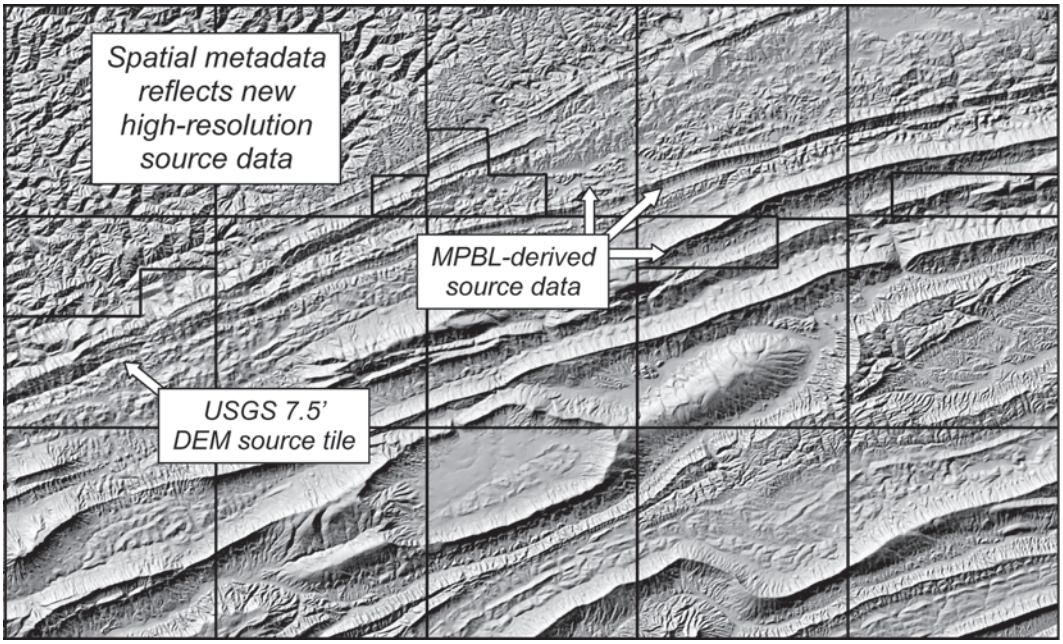

Figure 4.17 Attributed source data polygons (black lines) from the NED spatially referenced metadata indicate where new high-resolution source data have been used to produce the NED.

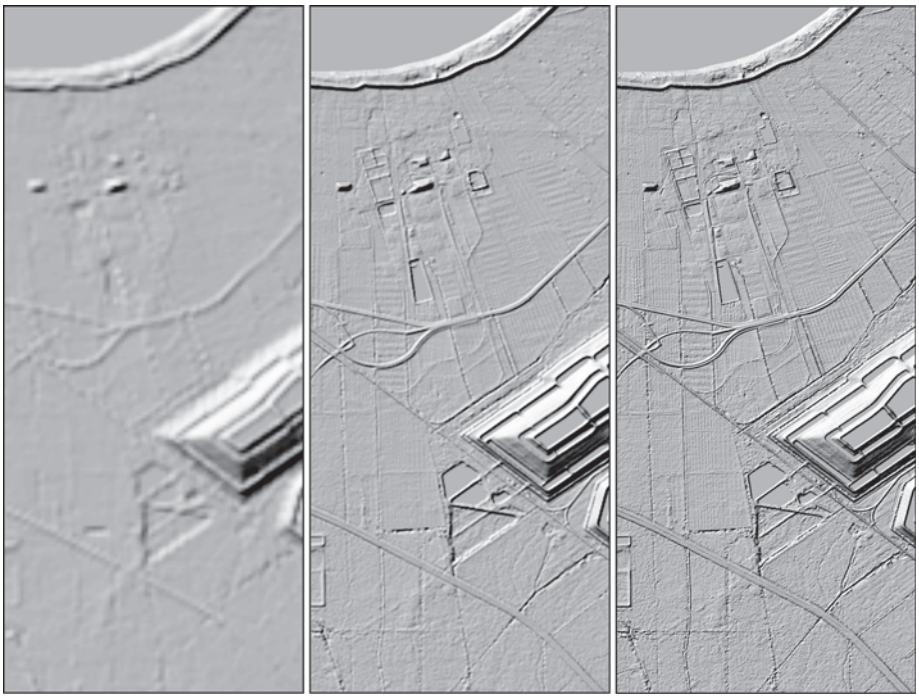

Figure 4.18 Multi-resolution NED layers for an area in Louisiana (1-arc-second data on the left; 1/3-arc-second data in the center; 1/9-arc-second data on the right). The source data for this area are lidar-derived elevation grids. The digital data for this example area are provided on the media accompanying this book.

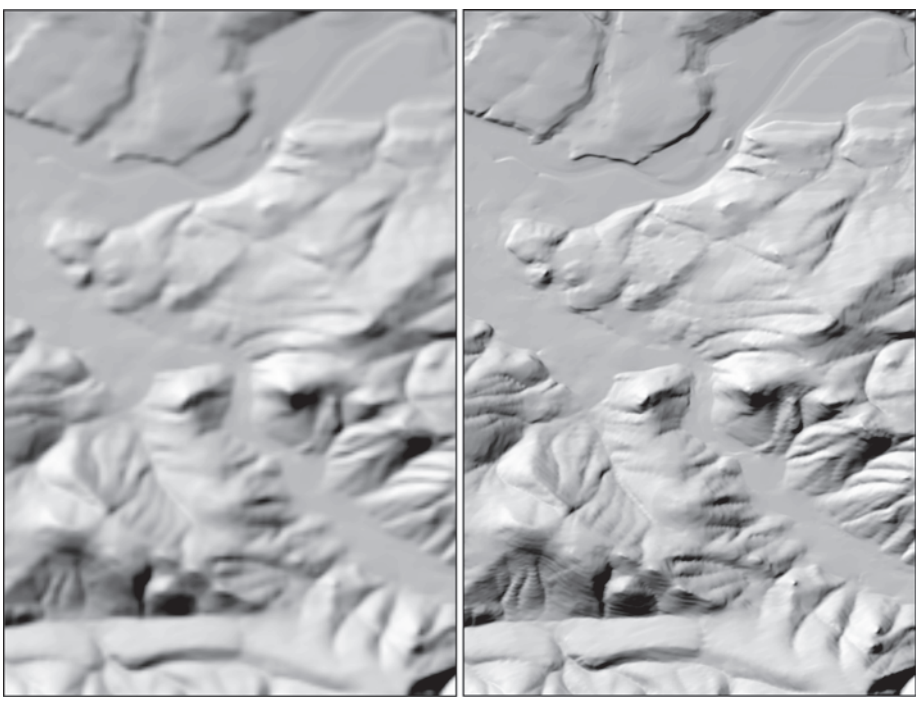

Figure 4.19 Multi-resolution NED layers for an area in western Montana (1-arc-second data on the left; 1/3-arc-second data on the right). The source data for this area are USGS 7.5-minute DEMs that were derived from 1:24,000-scale hypsography and hydrography through contour-to-grid interpolation. The digital data for this example area are provided on the media accompanying this book.

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