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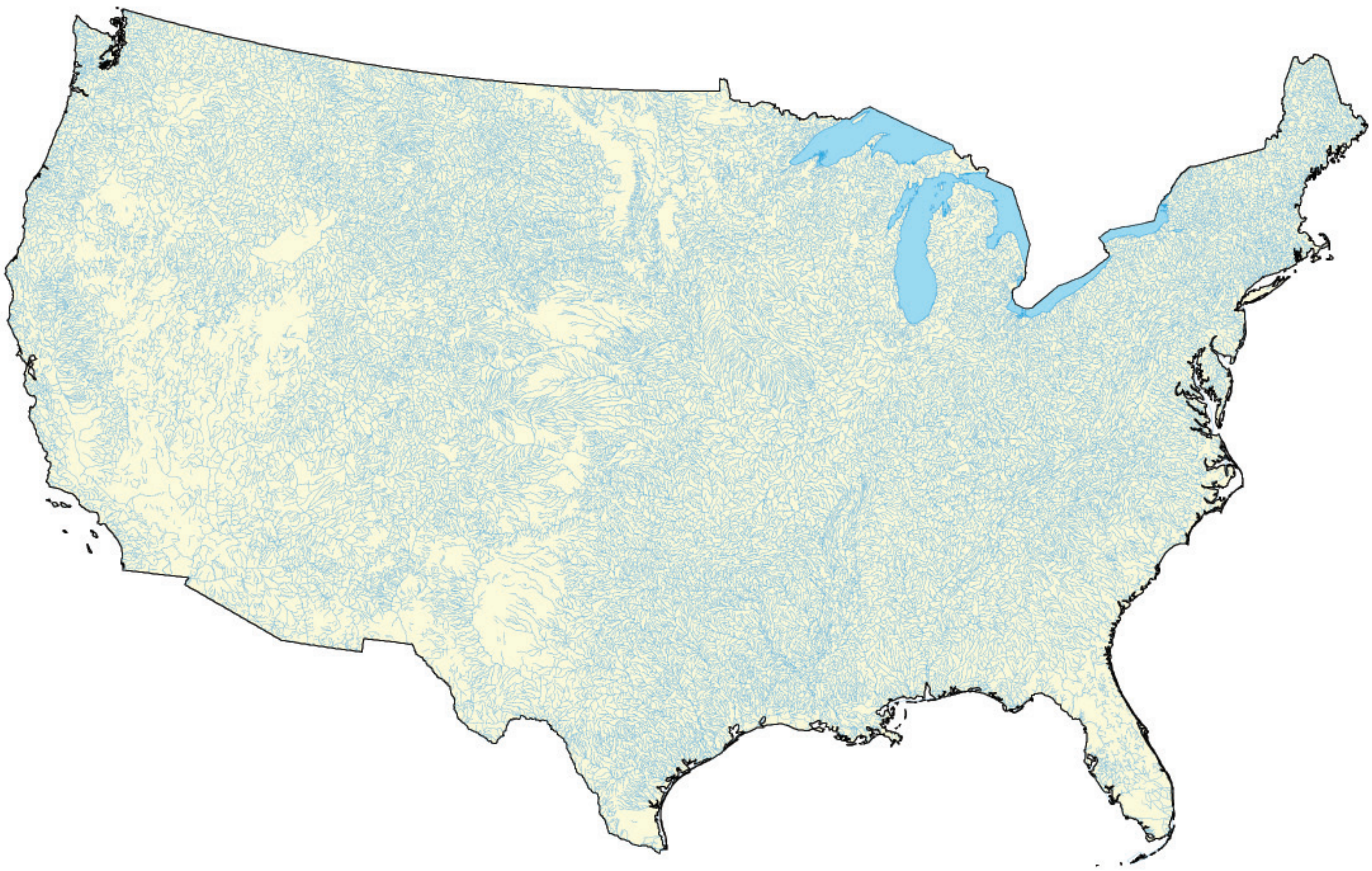
Production of a National 1:1,000,000-Scale Hydrography Dataset for the United States—Feature Selection, Simplification, and Refinement



Scientific Investigations Report 2009–5202
Revised May 2010

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

Front cover: 1:1,000,000-scale continental United States streams.

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By Robin H. Gary, Zachary D. Wilson, Christy-Ann M. Archuleta, Florence E. Thompson, and Joseph Vrabel

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Conversion Factors, Datum, and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)

Datum

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

Abbreviations

AGS	American Geographical Society
AMS	Army Map Service
DEM	Digital elevation model
DLG	Digital line graph
EDNA	Elevation Derivatives for National Applications
GNIS	Geographic Names Information System
IMW	International Map of the World
INEGI	Instituto Nacional de Estadística, Geografía e Informática (Mexico's National Institute for Statistics, Geography, and Informatics)
NED	National Elevation Dataset
NGA	National Geospatial-Intelligence Agency
NHD	National Hydrography Dataset
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VAA	Value-added attribute
VMAP0	Vector Map Level 0

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Abstract

During 2006–09, the U.S. Geological Survey, in cooperation with the National Atlas of the United States®, produced a 1:1,000,000-scale (1:1M) hydrography dataset comprising streams and waterbodies for the entire United States, including Puerto Rico and the U.S. Virgin Islands, for inclusion in the recompiled National Atlas. This report documents the methods used to select, simplify, and refine features in the 1:100,000-scale (1:100K) (1:63,360-scale in Alaska) National Hydrography Dataset to create the national 1:1M hydrography dataset. Custom tools and semi-automated processes were created to facilitate generalization of the 1:100K National Hydrography Dataset (1:63,360-scale in Alaska) to 1:1M on the basis of existing small-scale hydrography datasets. The first step in creating the new 1:1M dataset was to address feature selection and optimal data density in the streams network. Several existing methods were evaluated. The production method that was established for selecting features for inclusion in the 1:1M dataset uses a combination of the existing attributes and network in the National Hydrography Dataset and several of the concepts from the methods evaluated. The process for creating the 1:1M waterbodies dataset required a similar approach to that used for the streams dataset. Geometric simplification of features was the next step. Stream reaches and waterbodies indicated in the feature selection process were exported as new feature classes and then simplified using a geographic information system tool. The final step was refinement of the 1:1M streams and waterbodies. Refinement was done through the use of additional geographic information system tools.

Introduction

A 1:1,000,000-scale (1:1M) nationwide hydrography dataset is critical to meeting the evolving needs of the National Atlas of the United States® (National Atlas of the United States, 2008). Within the scope of the National Atlas, preparation, integration, and maintenance of national, small-scale (relatively large area) cartographic frameworks are essential to promoting collaboration, research, and cost savings across the spectrum of Federal geospatial and geostatistical data users and producers. The National Atlas fills the need for small-scale cartographic frameworks by collaborating with mapping agencies in Mexico and Canada on the 1:10,000,000-scale (1:10M) North American continental framework and by producing and maintaining the 1:2,000,000-scale (1:2M), and now the 1:1M framework datasets of the United States. Formal working relationships between the U.S. Geological Survey (USGS) and Instituto Nacional de Estadística, Geografía e Informática (INEGI, Mexico's National Institute for Statistics, Geography, and Informatics) and between the USGS and the Natural Resources Canada Earth Sciences Sector enable the three organizations to collaborate on the production and maintenance of the North American Atlas 1:10M datasets.

During 2006–09, as part of an effort to recompile National Atlas 1:2M data layers at 1:1M and fulfill the goal of the Global Mapping Initiative[1], the USGS, in cooperation with the National Atlas of the United States, produced a 1:1M hydrography dataset comprising streams and waterbodies (referred to as water courses and inland water in the Global Map). The focus of this production effort was to create datasets of 1:1M streams and waterbodies, with appropriate stream density, using a method for selecting features from the National Hydrography Dataset (NHD) (U.S. Geological Survey, 2008) that would be consistent across the entire United States and also would maintain network connectivity. Additionally, the vast cartographic knowledge embedded in the National Atlas and other datasets was to be retained.

Purpose and Scope

This report documents the methods used to select, simplify, and refine features in the 1:100,000-scale (1:100K) (1:63,360-scale in Alaska) NHD to create a national 1:1M hydrography dataset for inclusion in the recompiled National Atlas of the United States. The 1:1M hydrography dataset encompasses the entire United States, including Puerto Rico and the U.S. Virgin Islands. Using small-scale, ancillary datasets for reference, the features included in the 1:1M

[1] The goal of the Global Mapping Initiative is to develop a global coverage of 1:1M geographic datasets that include elevation, vegetation, land cover, land use, transportation, drainage systems, boundaries, and population centers. These datasets will facilitate environmental monitoring at a global scale.

hydrography dataset were selected using custom tools and semi-automated processes that leveraged the geometric network and detailed attributes available in the NHD. The features in the 1:1M streams and waterbodies datasets were simplified to create less complex features as well as to reduce storage requirements. Streams were refined to equalize areas of stream-density disparity and remove density artifacts (sometimes called map faults). Waterbodies were refined to adjust feature geometry and name attributes affected by different source maps.

Acknowledgments

The authors thank Anna Regan and Andrew Murray (Natural Resources Canada, Ottawa, Ontario, Canada) and José Luis Ornelas (INEGI, Aguascalientes, Aguascalientes, Mexico) for their work on harmonizing data along international boundaries, and Taro Ubukawa (Geographic Survey Institute of Japan, International Steering Committee for Global Mapping Secretariat) for his help distributing the Global Mapping Initiative data.

Feature Selection

Datasets

Several readily available, small-scale, nationwide hydrographic datasets exist, although none of these ancillary datasets singularly fills the needs of the National Atlas recompilation effort or the Global Mapping initiative specifications. National Atlas maintains 1:2M datasets of streams and waterbodies of the United States (National Atlas of the United States, 2006). The National Geospatial-Intelligence Agency (NGA) distributes the Vector Map Level 0 (VMAP0) datasets compiled at 1:1M (National Geospatial-Intelligence Agency, 1998). A variety of national mapping agencies produced paper map sheets at 1:1M for the International Map of the World (IMW) series (available at the USGS Library, Reston, Va.). The USGS Elevation Derivatives for National Applications (EDNA) dataset (U.S. Geological Survey, 2005a) is a multi-layered, 30-meter-resolution synthetic stream network database derived from the National Elevation Dataset (NED) (U.S. Geological Survey, 2006a) that includes hydrologic derivatives. Hydrologic derivatives are hydrologic characteristics of the land surface that have been calculated from a digital elevation model (DEM). The collaborative NHD program, led by the USGS, also provides large-scale (1:63,360) to intermediate-scale (1:100,000) surface-water data.

The features of the 1:2M datasets of streams and waterbodies of the United States were originally digitized by the USGS from the 21 general reference maps contained in “The National Atlas of the United States of America” published in hardcopy (U.S. Geological Survey, 1970). The 1:2M Digital Line Graph (DLG) data were merged into a single national water features dataset; then names, feature types, and geometry were updated using 1:250,000 (1:250K), 1:100K, and 1:24,000 (1:24K) USGS topographic maps. To avoid losing the cartographic information in the National Atlas 1:2M streams and waterbodies datasets, the 1:2M data were used as the highest priority source for feature selection for inclusion in the new 1:1M datasets. Features in the National Atlas 1:2M datasets are represented in the 1:1M datasets.

VMAP0 is an updated and enhanced version of the National Imagery and Mapping Agency (now NGA) Digital Chart of the World. The VMAP0 hydrographic dataset at 1:1M is based on source data collected from 1972 through 1992. The original data source for VMAP0 was the 1:1M Operational Navigational Chart series that was produced by the military mapping agencies of Australia, Canada, the United Kingdom, and the United States. VMAP0 data were used as the initial vector datasets in the Global Mapping Initiative so that national mapping agencies could verify and improve the existing data (Pearson and others, 2006).

The IMW series predates the Global Mapping Initiative as the first attempt to construct maps based on a common scale and universally accepted conventions. Maps from the IMW series were produced by numerous organizations from the 1910s to the 1970s and distributed as paper maps. A set of general standards guided extent, projection, content, and symbology. However, as more IMW maps were produced, maintaining consistency became increasingly difficult (Heffernan, 2002; Pearson and others, 2006). The 69 IMW maps that cover the continental United States, Alaska, and Hawaii were produced between 1934 and 1978 by the USGS, Army Map Service (AMS), American Geographical Society (AGS), and the Canada Department of Energy, Mines, and Resources (figs. 1, 2) (see “Selected References”). Each map contains similar content, but each varies in detail because of differences in source data used to compile the map and because of variance in standards used by the compiling agencies. The hardcopy IMW maps at the USGS Library in Reston, Va., were scanned and orthorectified using a minimum of 10 control points and a third-order polynomial transformation (ESRI®, 2008c).

The USGS distributes and maintains the EDNA dataset, the synthetic stream network derived from the NED. The NED is a seamless DEM composed of the highest-resolution and best-quality elevation data available for the Nation. The synthetic stream network is constructed by computing flow accumulation and flow direction, then deriving flow paths. Because the synthetic stream network depends on the resolution of the NED, scale is difficult to define for the derivative datasets; however, several derivatives can help indicate stream order. For example, one of the elevation derivative datasets estimates mean annual streamflow for the synthetic stream network by using catchment area and annual precipitation data.

The NHD is a nationwide surface-water dataset that includes networked flowlines (digital spatial data representing streams or canals) with flow direction available for intermediate (1:100K) to large (1:63,360) scales. The

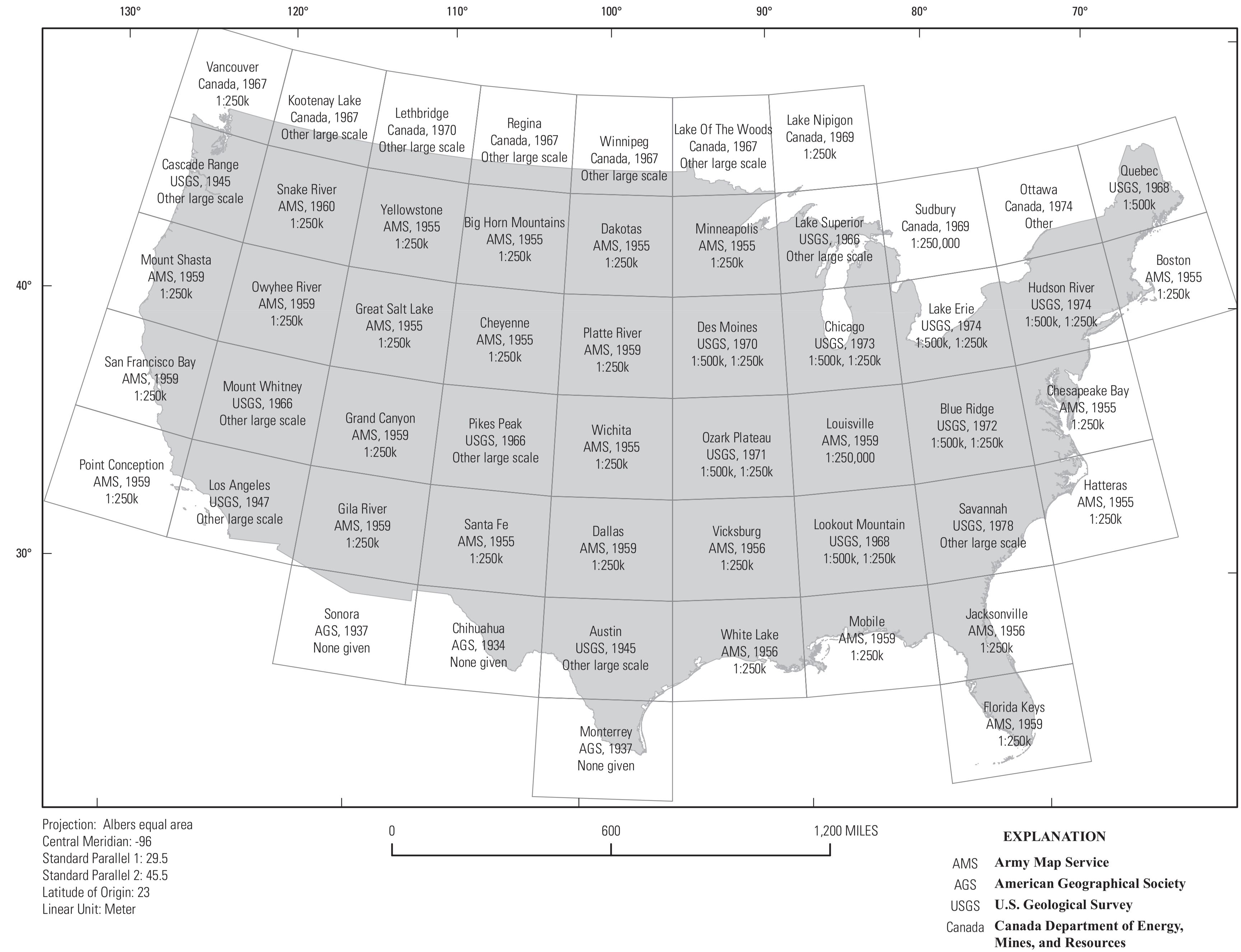

Figure 1. International Map of the World (IMW) map sheet index for the continental United States.

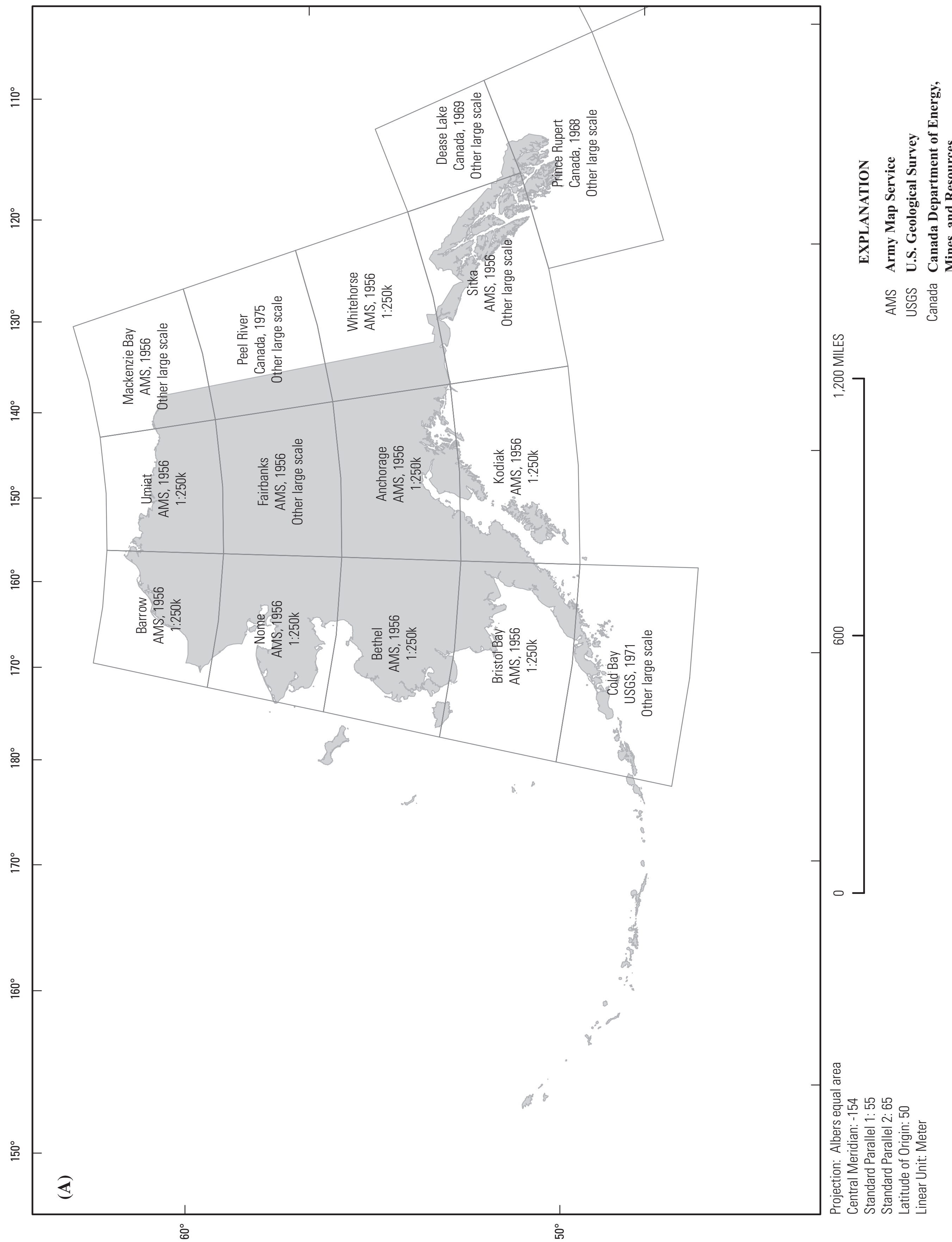

Figure 2. International Map of the World (IMW) map sheet index for (A) Alaska and (B) Hawaii.

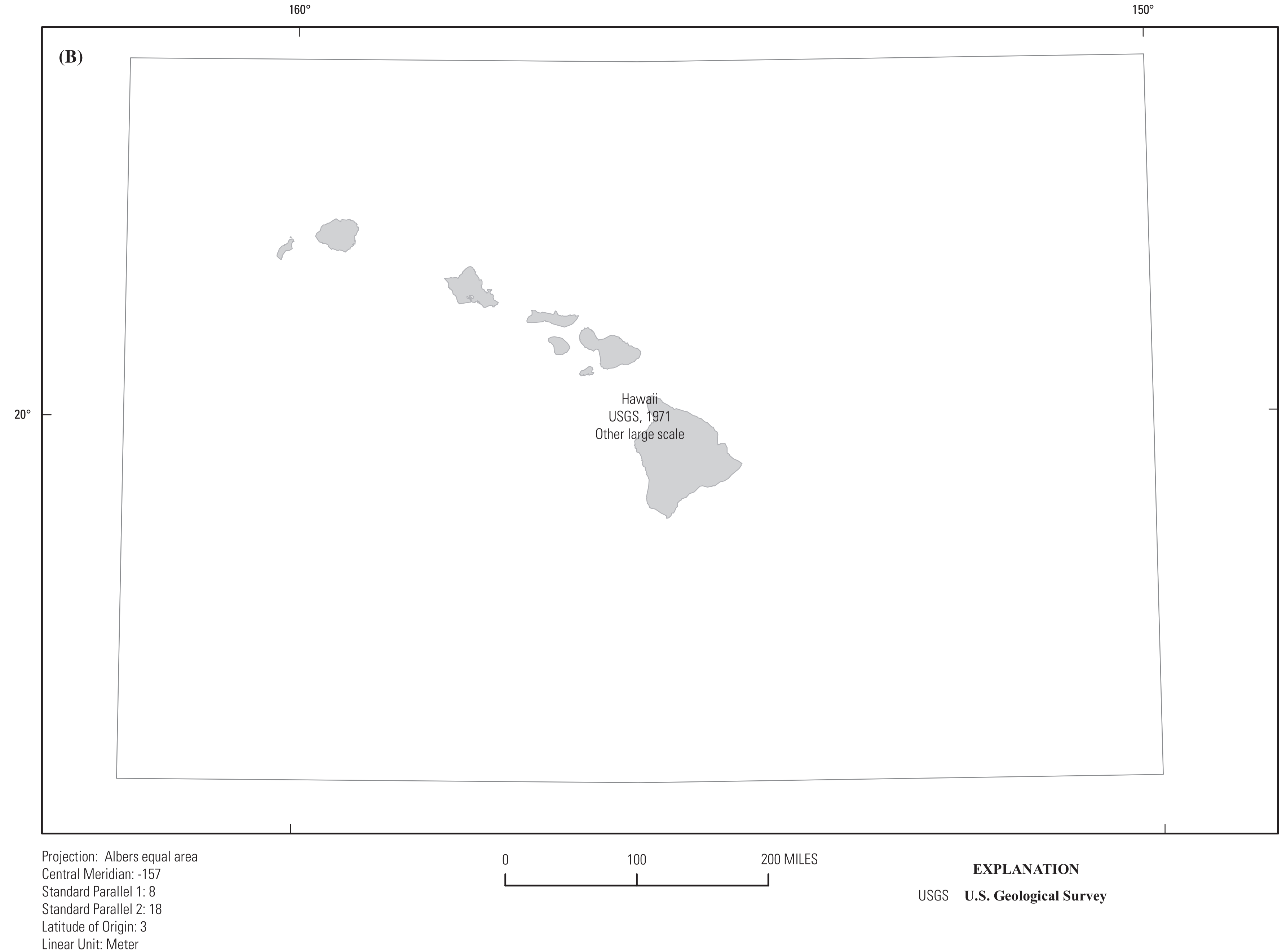

Figure 2. Continued.

intermediate-scale dataset for the continental United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands (U.S. Geological Survey, 2006b) and the large-scale dataset for Alaska (U.S. Geological Survey, 2006c) were used as base data to compile the 1:1M hydrography dataset. To facilitate discussion in this report, the 1:100K and 1:63,360-scale datasets used to compile the 1:1M hydrography dataset are referred to as the NHD. The NHD contains several feature classes; the flowline and waterbodies feature classes were used as the source data to create the 1:1M streams and waterbodies datasets, respectively. The NHD is based on the DLG hydrography data that were digitized from USGS topographic maps. The DLG hydrography data were integrated with information from the U.S. Environmental Protection Agency (USEPA) Reach File Version 3 (U.S. Environmental Protection Agency, 1994) and then structured into a geometric network to allow for flow analysis. Reach codes were transferred from the USEPA Reach File Version 3 to help identify reaches (segments) in the flowline dataset in hydrologic analysis. The flowline attributes include reach codes, feature type, flow direction, Geographic Names Information System (GNIS) (U.S. Geological Survey, 2007) name, and length in kilometers. Datasets are available in ESRI personal geodatabase format by subregion, also known as 4-digit hydrologic unit codes. Two-hundred twenty-two subregional personal geodatabases cover the 21 regions in the continental United States, Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands. The NHD is an ideal source dataset from which to derive the smaller-scale (1:1M) dataset because of the functionality of the geometric network and the wealth of feature-level attributes.

None of these sources individually provides the detail and accuracy needed to fulfill the requirements of the National Atlas recompilation effort or the Global Mapping Initiative. However, the existing small-scale datasets combine to form an appropriate indicator of stream network density. The accuracy, detail, and connectivity available in the NHD provide an appropriate and reliable base for the creation of a 1:1M hydrographic dataset. The NHD data model can be generalized by referencing ancillary small-scale data that cover the United States and its territories.

Streams

The first step in creating the new 1:1M dataset was to address feature selection and optimal data density in the streams network. The resources necessary for selecting features from the 222 subregional personal geodatabases of the NHD based on manual editing would have been prohibitive; thus the necessity of developing custom tools and semi-automated (partially software driven, partially manual editing) processes. Programmatically automated methods for stream selection and delineation have been developed by others, including those described by NHD*Plus* (U.S. Environmental Protection Agency and U.S. Geological Survey, 2008); EDNA (U.S. Geological Survey, 2005a); and Stanislawski and others (2005).

During a prototyping phase, several methods of feature selection were evaluated. The features selected or delineated using previously developed semi-automated methods were either insufficiently consistent at 1:1M or the methods were too data- and time-intensive to meet production needs. The production method that was established combined the most effective aspects of the evaluated methods to facilitate production on a national scale and to minimize the need for post-selection manual quality assurance.

Methods Evaluated

Utility Network Analyst

The ArcGIS Utility Network Analyst™ (ESRI, 2008a) allows the user to trace downstream on any dataset that contains a geometric network. The NHD geodatabases have a built-in geometric network that stores the directionality of each line feature within a feature class as well as the relation of the feature to flow through the network. By placing a flag on a headwater reach, flow can be traced downstream to the outlet of the network. The results of the trace can be converted to a selection of features, the attributes of which can then be updated. In test cases, streams for the 1:1M dataset were selected using the trace downstream available through the Utility Network Analyst. In areas with divergent streamflow and areas with braided streams, segments in all stream paths were selected instead of just the segments that composed the main flow path. The NHD geometric network greatly increases analysis capabilities, without which the production of the 1:1M dataset would have taken much longer. However, the Utility Network Analyst tracing capabilities were insufficient to meet production needs.

Geographic Names Information System Names Hierarchy

NHD streams have a name attribute that is populated by the official geographic name registered in the GNIS. The GNIS Names Hierarchy method used the number of stream segments with the same name, as indicated by the GNIS attribute, to determine whether to include them in the 1:1M dataset. This counting procedure aimed to establish a hierarchy such that small streams with only one or two named segments were not selected for inclusion in the 1:1M dataset. A relative threshold value for the number of stream segments with a particular GNIS name was estimated by comparing density to ancillary maps compiled at 1:1M; however, this estimation technique limited repeatability because the threshold value is subjective. Results of the selection procedure contained breaks in network connectivity caused by missing GNIS name attributes. Additionally, the resulting stream density from this selection procedure was inconsistent between datasets because of the variability of GNIS-name attribute density across the country. For example, more NHD streams might have GNIS name attributes in and near urban areas, and streams in rural areas might have fewer GNIS names.

Resulting stream density also might be inconsistent because more complicated stream networks with smaller named segments could be weighted more heavily than less complicated stream networks. Even if stream names were weighted by length instead of number of segments, the GNIS name attributes in NHD were not extensive enough to make name-hierarchy analysis feasible as a stand-alone selection procedure. However, the names were an important part of the production method that was established for selecting streams for inclusion in the 1:1M dataset.

Hydrologic Derivatives

Hydrologic derivatives are hydrologic characteristics of the land surface that have been calculated from a DEM. One important hydrologic derivative is flow accumulation, which is calculated by summing the number of cells that flow into each cell. The value recorded for a cell represents the total number of cells in the DEM that contribute flow to that cell. Flow-accumulation values can indicate the relative hydrologic importance of a cell in a watershed. A cell with high flow-accumulation value might indicate that the cell corresponds spatially to a feature in the NHD that should be included in the 1:1M dataset. Calculation of hydrologic derivatives, including flow accumulation, can be time- and data-intensive. Production benefited greatly from the hydrologic derivatives in the EDNA dataset that were calculated from the 30-meter-resolution NED.

Because flow-accumulation values can indicate the relative importance of a stream within a watershed, the NHD and EDNA flow-accumulation values were analyzed to establish a relation between the two datasets. Buffers of various sizes were created for all NHD streams and then used to extract statistics from the flow-accumulation raster data. The statistical profile of each reach was then used to rank the streams and determine whether a stream should be included in the 1:1M dataset. Results of this method were then compared to the National Atlas 1:2M, VMAP0 1:1M, and IMW 1:1M datasets. This approach was successful in selecting reaches that correlated with the 1:1M ancillary datasets in the middle parts of watersheds but was less successful in selecting important headwater reaches and reaches in areas with low topographic relief. The EDNA flow-accumulation raster data alone were insufficient for determining which streams should be included in the 1:1M dataset; however, flow accumulation became an important factor either for selecting headwater reaches when the other ancillary datasets were ambiguous about which headwater reach was most important or for determining the preferred downstream path in cases where there were multiple downstream reaches.

NHD*Plus* Thinner Code

The USEPA, USGS, and Horizon Systems Corporation developed NHD*Plus*, a networked hydrographic dataset with value-added attributes (VAAs) based on the 1:100K NHD. Among the VAAs is a Thinner Code attribute, which is designed to allow the user to progressively thin the representation of the hydrographic network by selecting among seven values (0–6). If values 0–6 are represented in the network, all reaches will be present. Starting with the Thinner Code value of 6, the network can be thinned by eliminating more Thinner Code values from the cartographic representation. Here, the goal was to select reaches to represent a 1:1M network; however, the NHD*Plus* Thinner Code values were not consistent enough across the United States to be used as the method for feature selection. Furthermore, the NHD*Plus* documentation advises that Thinner Codes “are designed to be used for improving the performance of Web pages” and “they should not be used for stream classification or analysis” (U.S. Environmental Protection Agency and U.S. Geological Survey, 2008, p. 67). Thus the existing Thinner Code attribute was judged inadequate for feature selection.

Established Production Method

The production method that was established for selecting streams for inclusion in the 1:1M dataset uses a combination of the existing attributes and network in the NHD and several of the concepts from the methods evaluated. Headwaters were selected on the basis of published small-scale datasets, a downstream trace algorithm used the existing network in the NHD to select the downstream reaches, and then selection decisions that could not be automatically calculated were edited manually (fig. 3). In cases where streams are divergent or braided, the downstream trace algorithm selected reaches that form a preferred path among the available paths for accurate representation of streams at 1:1M. All decisions to include a reach in the final 1:1M dataset, regardless of whether they were made manually or automatically, were documented at the feature level by a reason code (table 1). The production method for stream and waterbody selection thus relied on hierarchical rules for feature selection and was implemented using automated and manual methods that reduced human error, increased repeatability, and facilitated feature-level documentation.

Headwater Selection

Headwater reaches were selected manually on the basis of whether the stream was represented in the National Atlas, VMAP0, and IMW hydrography datasets, which served as primary indicators of 1:1M stream density. For example, if a headwater reach in NHD coincided spatially with a headwater reach in the National Atlas, then that NHD headwater reach was attributed for inclusion in the 1:1M dataset. Occasionally, either National Atlas, VMAP0, or IMW data did not indicate a particular headwater, resulting in more than one headwater reach that could be included in the 1:1M dataset. In these cases, the NHD headwater reach with a name attribute present was attributed for inclusion in the 1:1M dataset. If no name attributes were present among

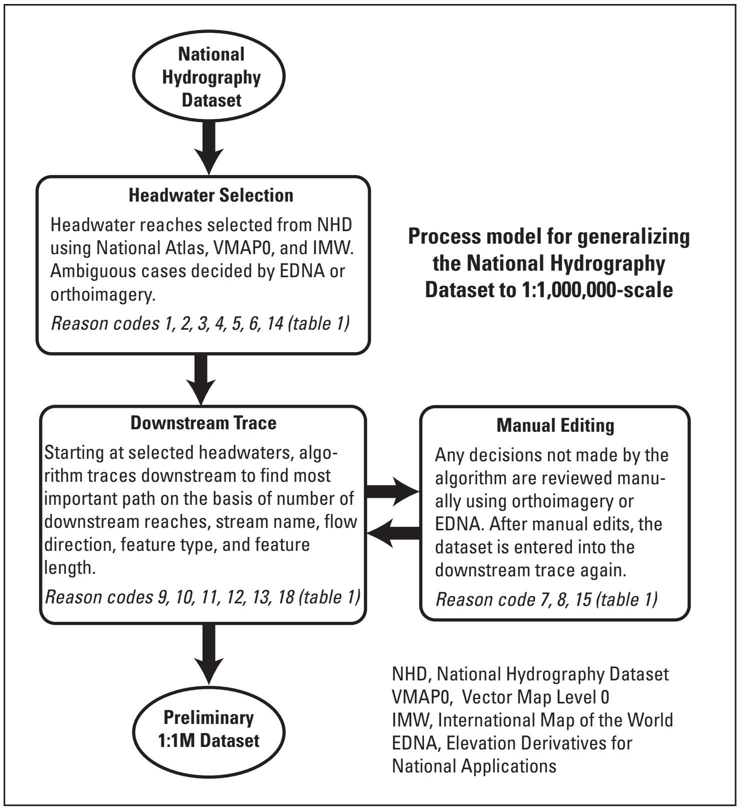

Figure 3. General processing steps required to select National Hydrography Dataset stream features for inclusion in the 1:1,000,000-scale streams dataset.

Table 1. Codes used to document reach selection for the 1:1,000,000-scale streams dataset.

[1:1M, 1:1,000,000-scale; HS, headwater selection; VMAP0, Vector Map Level 0; EDNA, Elevation Derivatives for National Applications; ME, manual editing; DT, downstream trace; GNIS_ID, Geographic Names Information System identification number; IMW, International Map of the World]

Reason	Description	Processing	Number of features
0	Not a 1:1M stream (default value)	Preprocessing	0
1	National Atlas	HS	7,772
2	VMAP0	HS	9,591
3	National Atlas and VMAP0	HS	8,916
4	National Atlas and EDNA	HS	250
5	VMAP0 and EDNA	HS	254
6	National Atlas, VMAP0, and EDNA	HS	246
7	EDNA	ME	877
8	Orthoimagery	ME	1,910
9	Only downstream reach	DT	952,087
10	GNIS_ID equivalent to upstream reach	DT	78,893
11	Only downstream reach with GNIS_ID	DT	359
12	Only downstream reach classified as stream	DT	1,343
13	Only downstream reach with flow direction	DT	1,776
14	IMW	HS	26,324
15	Digital topographic maps	ME	2,050
18	Shortest segment	DT	11,712
99	Manually excluded	ME	0

the possible headwater reaches, then the USGS EDNA data and digital orthoimagery were used to select the appropriate headwater reach. After all headwater reaches were attributed, a downstream trace tool was used to update attributes throughout the rest of the stream network.

Downstream Trace Algorithm

The downstream trace algorithm used was written in Visual Basic for Applications using ArcObjects (ESRI, 2006) and implemented as an easy-to-use tool within the ArcMap™ (ESRI, 2007) environment. The algorithm considers flow direction, number of adjacent downstream reaches, stream names, and feature type (for example, stream, canal, or artificial path) to extract preliminary 1:1M flow paths from the NHD (fig. 4) for inclusion in the 1:1M dataset. As the tool traces downstream, if there is only one downstream reach, it is included in the 1:1M dataset; the next downstream reach is analyzed in the same manner. When there is more than one downstream reach, the tool references a set of criteria to decide which of the downstream reaches should be included in the 1:1M dataset. Priority is given to officially named segments, segments coded as streams, and segments with flow direction, respectively. Once the preferred downstream reach is determined, the tool examines the next downstream reach in the same manner.

Manual Editing

If the downstream reach does not meet any of the selection criteria, the downstream trace algorithm stops processing to allow the analyst to select the appropriate downstream reach on the basis of digital orthoimagery, georeferenced topographic maps, or the EDNA dataset. After all reaches are updated, the dataset is then reevaluated by the algorithm to continue tracing downstream. The extent to which manual editing was required depended on the characteristics of the NHD in a particular subregion. Subregions with extensive

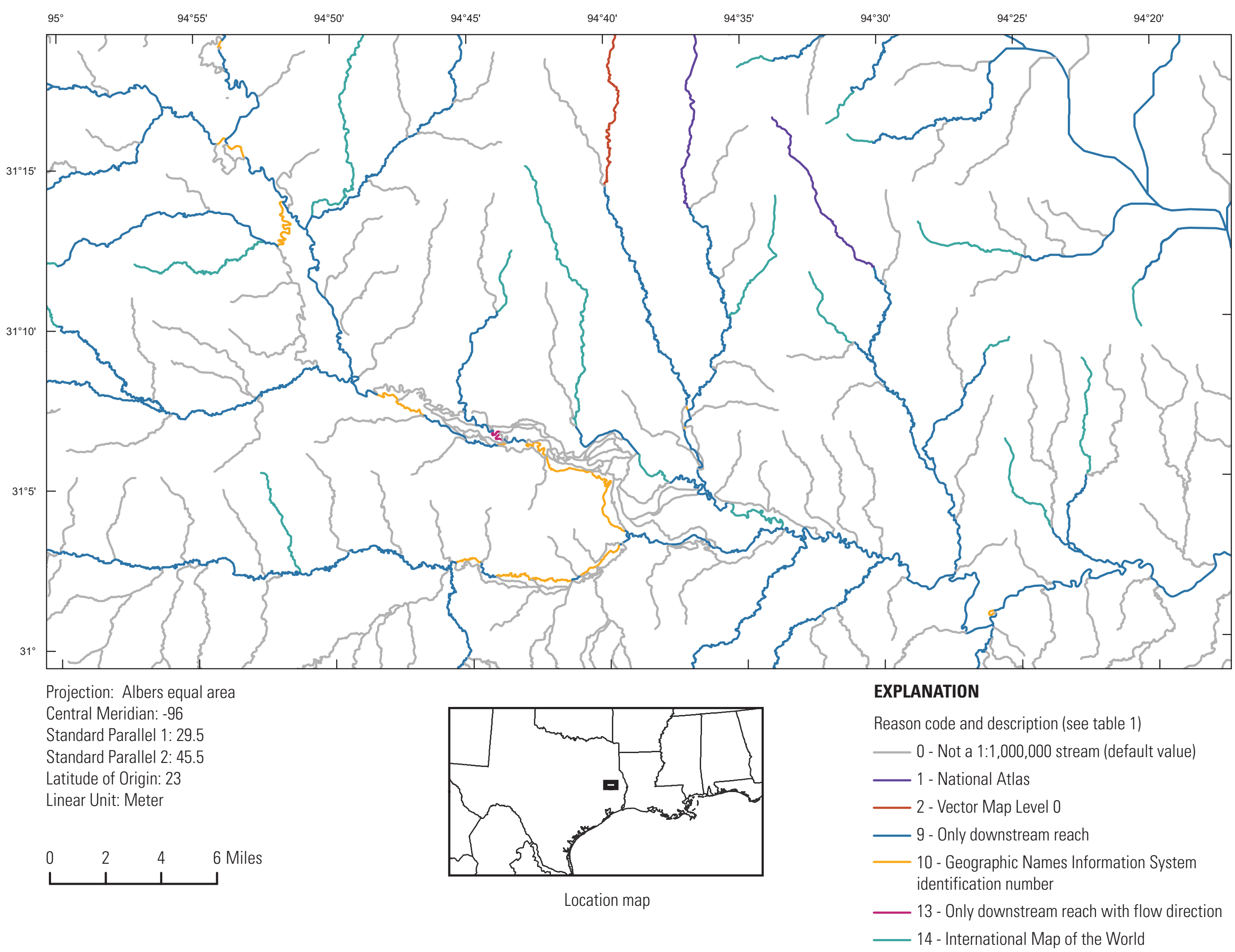

Figure 4. Reaches symbolized using the feature-level metadata that document why individual reaches were included in the 1:1,000,000-scale streams dataset.

GNIS names, for example, were less likely to need manual editing.

Quality Assurance

After all reaches were selected, the proposed 1:1M network was examined for connectivity. Headwater selections were confirmed independently by another analyst. Hydrologic connectivity was checked visually and by tracing upstream on the network to identify reaches that needed to be added manually. Any gaps in the network were closed using the same method of feature selection described above in the “Established Production Method” section.

Waterbodies

The process for creating the 1:1M waterbodies dataset required a similar approach to that used for the 1:1M streams dataset. First, the 1:2M content represented in the National Atlas needed to be preserved in the new 1:1M dataset. Second, additional waterbodies needed to be selected from the NHD to represent 1:1M requirements.

Methods Evaluated

The NHD waterbodies are not part of a geometric network, so automating the selection process was limited to location or feature attributes, or both. Because the 1:1M waterbodies dataset should represent waterbodies in the National Atlas 1:2M waterbodies dataset and add detail, selection by locating where waterbodies coincided with National Atlas and VMAP0 waterbodies was attempted; NHD waterbodies that intersected waterbodies represented in National Atlas and VMAP0 were selected. In several cases, spatial shifts or offsets in the VMAP0 waterbodies dataset were substantial enough that the intersection was not efficient at selecting the NHD waterbody polygons that correlated with VMAP0 waterbodies. The spatial shifts in the VMAP0 dataset made selection by location inconsistent, so location could not be the sole selection criterion.

Established Production Method

The production method that was established for selecting waterbodies for inclusion in the 1:1M dataset combined a waterbody area threshold with manual verification and addition of features represented in the National Atlas 1:2M waterbodies dataset. An area threshold was used to automate waterbody selection. Different thresholds were tried until a minimum area was determined that resulted in selection of most waterbodies represented in the National Atlas 1:2M waterbodies dataset. Waterbodies with an area greater than 1 square kilometer (0.3861 square mile) were selected and included in the 1:1M selection, then waterbodies with an area greater than 0.5625 square kilometer (0.2172 square mile) that coincided with National Atlas 1:2M waterbodies were manually added to the selection.

Simplification

Geometric simplification of features commonly is done to create less complex lines for maps or to reduce data storage requirements (Neuffer and others, 2004). The features in the 1:1M streams and waterbodies datasets were simplified to create less complex features as well as to reduce storage requirements. One use of the 1:1M streams and waterbodies datasets is for cartographic representation, which requires that the features display an appropriate level of detail at 1:1M. Additionally, the 1:1M streams and waterbodies datasets are intended to facilitate hydrologic analysis, so the simplification process cannot disable networking capabilities. Simplification of features reduces the size of the dataset, which makes data transfer and analysis more efficient. Feature geometry thus was simplified for increased usability and processing speed. Another option would have been to keep the geometry as detailed as possible and allow the user to simplify as necessary.

Reaches indicated in the feature selection process were exported as a new feature class and then simplified using the Bend Simplify algorithm of the ESRI Simplify Line tool (ESRI, 2008b) with a tolerance of 500 meters. The Bend Simplify algorithm modifies the line geometry between end nodes by analyzing and modifying non-critical bends relative to a semicircle with a radius of 500 meters. The result is a simplified line that maintains the general shape of the original segment without moving the end nodes. The segment end nodes were preserved to maintain the importance of the reach codes. Combining and merging contiguous segments would greatly reduce file size by allowing more geometric simplification, but the reach codes are an important aspect of the stream network that allow for hydrologic analysis. The new, simplified and generalized subregional streams dataset was appended into a regional streams feature class and then tested for network connectivity. A new regional geometric network was created, and upstream traces were used to search for missing or disconnected reaches.

Similarly, waterbodies were simplified using the Bend Simplify algorithm of the ESRI Simplify Line tool (ESRI, 2008b) with a tolerance of 500 meters (fig. 5). The simplification process occasionally caused topological errors where the modified waterbody boundaries overlapped adjacent waterbodies or where slivers (thin, erroneous features) were introduced between waterbodies that share a boundary. The new, simplified and generalized subregional waterbodies datasets were appended into a regional waterbodies feature class and tested for topological errors. Waterbodies that overlapped other waterbodies and slivers along shared waterbody boundaries were corrected.

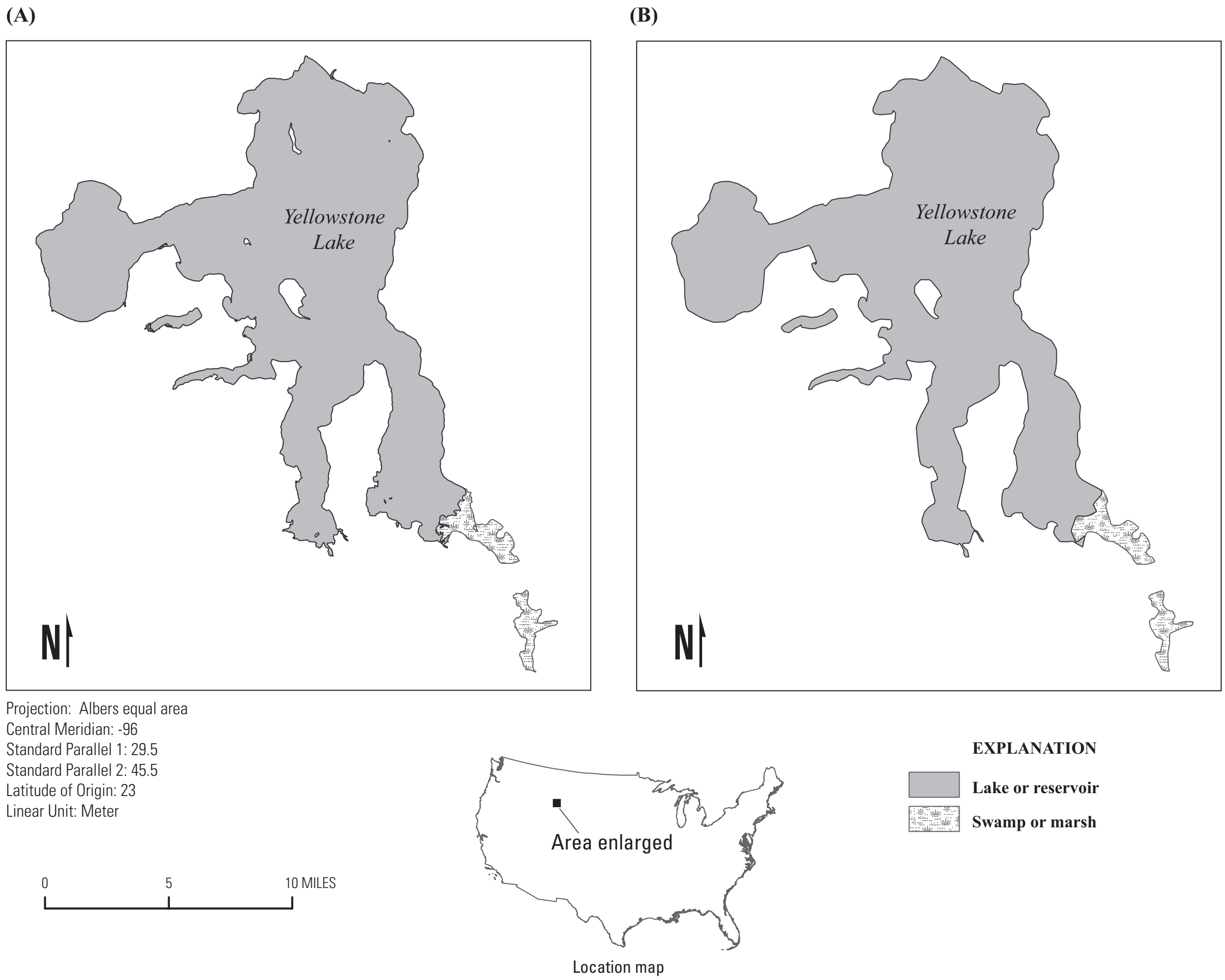

Figure 5. (A) Original National Hydrography Dataset 1:100,000-scale waterbody polygon with 2,297 vertices and (B) simplified 1:1,000,000-scale waterbody polygon with 1,032 vertices.

Refinement

Streams

After selecting streams from the NHD for the 1:1M dataset, areas of stream-density disparity were apparent in the stream network when viewing the dataset at a regional scale. These areas of disparity followed the boundaries of the IMW map sheets. Maps covering the United States in the IMW series (figs. 1, 2) were compiled during 1934–78 by four different agencies. As a result, the density of the stream network can differ from map to map, which means that the streams at the boundaries of each map do not always exactly match those at the boundaries of adjoining maps. When the paper maps were scanned and mosaicked, artifacts (sometimes called map faults) from the artificial boundaries between each map in the series were evident. These map faults occurred in areas where the density of cartographically represented physical features on one map was distinctly different from the density of such features on adjoining maps.

Because streams were selected for the 1:1M dataset partly on the basis of whether they were on an IMW map sheet, artifacts of the stream-density disparity carried over to the 1:1M hydrography dataset (fig. 6). Because the 1:1M dataset is intended to fill the needs for cartographic products and hydrologic analysis, density artifacts needed to be removed and stream density needed to be equalized across IMW boundaries. The density disparity was analyzed using the ratio of the 1:1M stream density to the National Atlas 1:2M stream density within polygons that resulted from the intersection of the NHD subregion boundaries and the IMW sheet boundaries. After the densest areas were identified and quantified with this ratio, streams were prioritized and selected streams were removed in these dense areas to create a uniform appearance across the stream network at a regional scale.

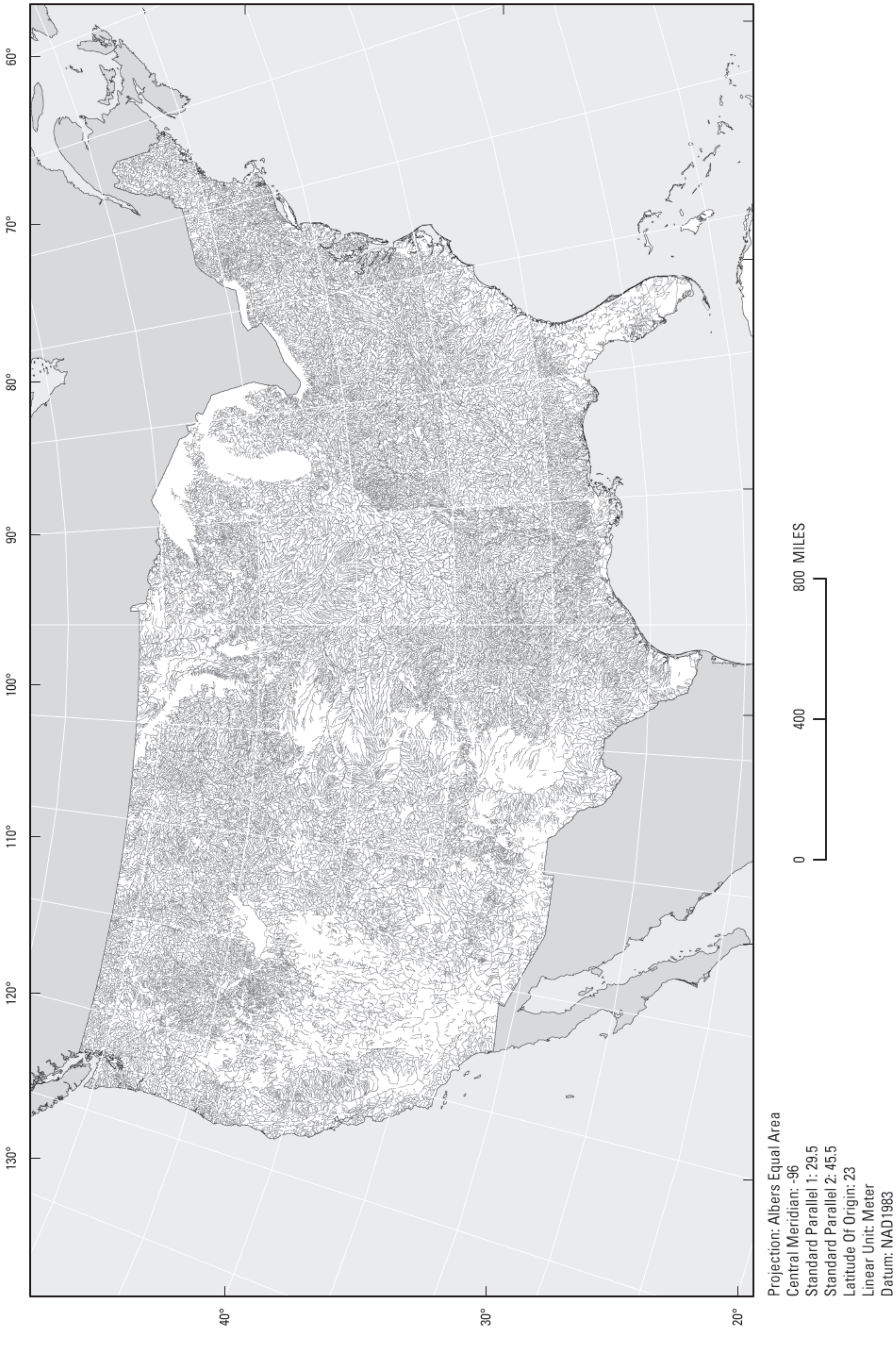

Figure 6. Preliminary 1:1,000,000-scale streams dataset showing stream-density disparity along adjoining boundaries of International Map of the World map sheets, continental United States.

Stream-Density Analysis

The stream-density disparities were visibly apparent (fig. 7A), but to follow an objective, repeatable process, the disparities needed to be quantitatively described and identified. The NHD subregion boundaries were intersected with the IMW map sheet boundaries to create polygons for analysis of the density disparities in the unrefined 1:1M dataset. Density of streams was calculated for the 1:1M unrefined dataset and the National Atlas 1:2M dataset in each of the density analysis polygons. Stream density is defined as the total linear length, in kilometers, of all streams in a density polygon divided by the density polygon area, in square kilometers.

The National Atlas 1:2M and the NHD 1:100K streams datasets represent water features in different ways. For example, large streams have a right and left bank in the National Atlas streams dataset, and they are represented as a single flowline in the NHD that might or might not have a corresponding NHD waterbody. To facilitate comparison of 1:1M stream density to National Atlas 1:2M stream density, the National Atlas 1:2M streams lengths were adjusted and normalized using feature types to apply weighting factors to be comparable to the NHD feature types (table 2). After the density of streams was calculated, the ratio of 1:1M stream density to 1:2M stream density was analyzed. Regions requiring density reduction were identified on the pre-refinement map (fig. 8A) as areas with high-density ratios adjacent to areas with low-density ratios that share a rectilinear boundary. High-ratio regions on the pre-refinement map indicate that the preliminary 1:1M streams dataset might be too dense compared to the National Atlas 1:2M streams dataset.

Stream-Density Adjustment

After the densest regions were identified, streams were removed from the 1:1M dataset in those regions to create a more uniform level of stream density. Streams were selected to be removed on the basis of indicated flow (perennial or intermittent), name attributes, and length to confluence. The headwater reach of a stream to be removed was selected, and then a tool traced the network downstream from the selected reach to the first confluence, removing the connected segments along the way. After selected reaches were removed, another tool was used to clean up any small headwater reaches that might have been missed in the removal process. Removing the selected streams resulted in stream density of the 1:1M dataset more closely matching that of the National Atlas 1:2M streams (figs. 7B, 8B).

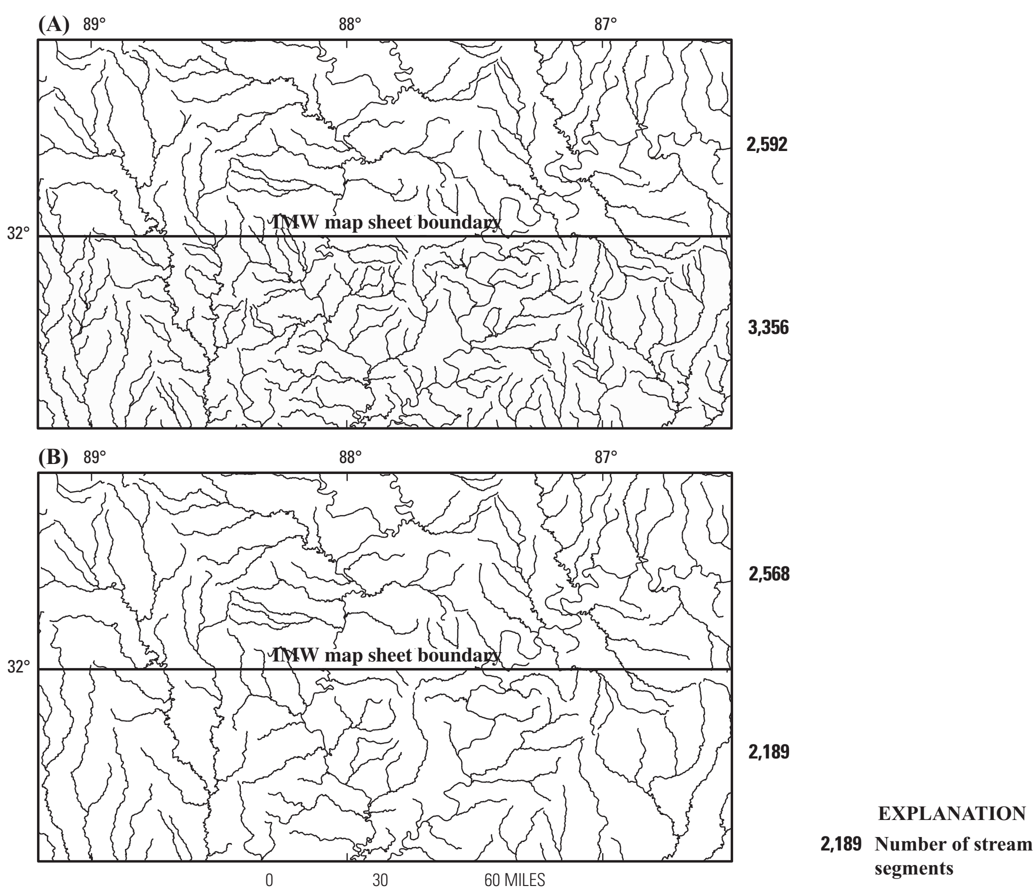

Figure 7. Example of stream-density disparity along International Map of the World (IMW) map sheet boundary (A) before and (B) after refinement of the 1:1,000,000-scale streams dataset.

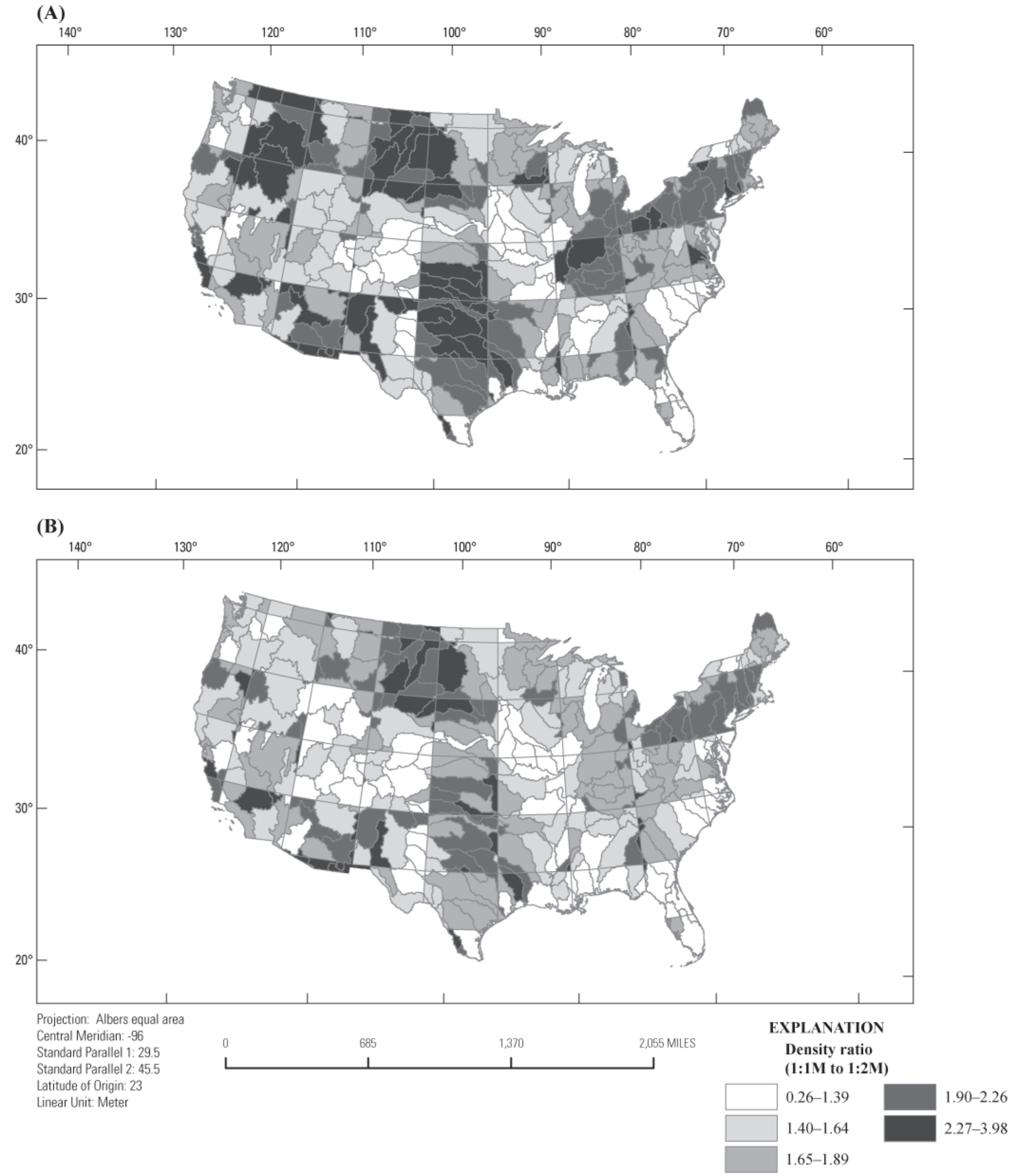

Figure 8. Density discrepancy polygons (based on intersection of International Map of the World map sheet boundaries and National Hydrography Dataset subregion boundaries) symbolized by the ratio of density in the 1:1,000,000-scale (1:1M) stream network to density in the National Atlas 1:2,000,000-scale (1:2M) stream network (A) before and (B) after refinement of the 1:1M streams dataset.

Table 2. Weighting factors used to adjust National Atlas 1:2,000,000-scale streams features to allow for comparison to 1:1,000,000-scale streams.

[NHD, National Hydrography Dataset]

Feature type	Weighting factor	Rationale
Apparent limit	Omit	Not present in NHD flowline
Aqueduct	Omit	Not present in NHD flowline
Canal	1	Equivalent features in NHD flowline
Canal intermittent	1	Equivalent features in NHD flowline
Closure line	Omit	Not present in NHD flowline
Dam	Omit	Not present in NHD flowline
Falls	Omit	Not present in NHD flowline
Intracoastal waterway	1	Check if in NHD
Left bank	.5	Assumes parallel stream banks, on average
Right bank	.5	Assumes parallel stream banks, on average
Shoreline	.3	Assumes approximate circular waterbody, on average
Shoreline intermittent	.3	Assumes approximate circular waterbody, on average
Stream	1	Equivalent features in NHD flowline
Stream intermittent	1	Equivalent features in NHD flowline
Braided stream	1	Equivalent features in NHD flowline
Null	Omit	Not present in NHD flowline

The last step in the density-adjustment process for streams was to plot all 1:1M streams for review by cartographers. The cartographers examined the density of the streams and determined whether streams should be added to or deleted from the 1:1M dataset. Using their knowledge of United States streams and referencing State base maps and other sources, the cartographers added a final level of refinement to the 1:1M streams dataset (fig. 9).

Evaluation of Stream-Density Adjustment

After the initial analysis of stream density and the subsequent adjustment of density along the map faults, the resulting density ratios were statistically analyzed to evaluate the results for consistency across the dataset. Because some of the density polygons were relatively small compared to the majority of the density polygons, a small number of outlying density ratios were present. Consequently, the upper 2 percentiles of the adjusted and unadjusted density ratios were removed from the analysis described here.

Summary statistics of the density ratios before and after adjustment are tabulated in table 3. All density ratios and computed statistics are reported to three significant figures. Quantitatively, 90 percent of the unadjusted density ratios are within the range of 0.750–2.94 about the median value of 1.77; 90 percent of the adjusted density ratios are within the range of 0.822–2.45 about the median value of 1.62. A common expectation would be that a 1:1M map would have about twice the “detail” of a 1:2M map. The unadjusted density ratio mean is 1.82 and the adjusted density mean is 1.64—both approaching a mean of 2. The density differences likely are due to the subjective interpretation of the 1:2M and 1:1M map compilers and the nature of the features in the base data.

To illustrate the adjusted and unadjusted density-ratio distributions, superimposed histograms were created (fig. 10). The overall range of the density ratios (0 to 4.73) was equally divided into 50 partitions (bins), and frequency counts were computed for each bin. Area-weighting (rescaling in proportion to density polygon area) was done on the computed frequency counts. In this manner, each density ratio is represented in proportion to its contributing area to the dataset. Using the means and standard deviations of the unadjusted and adjusted density ratios, theoretical normal distributions (probability density functions) were fit to the histograms (Helsel and Hirsch, 2000). Because the theoretical distributions are in probability space, the frequency counts of the histograms were

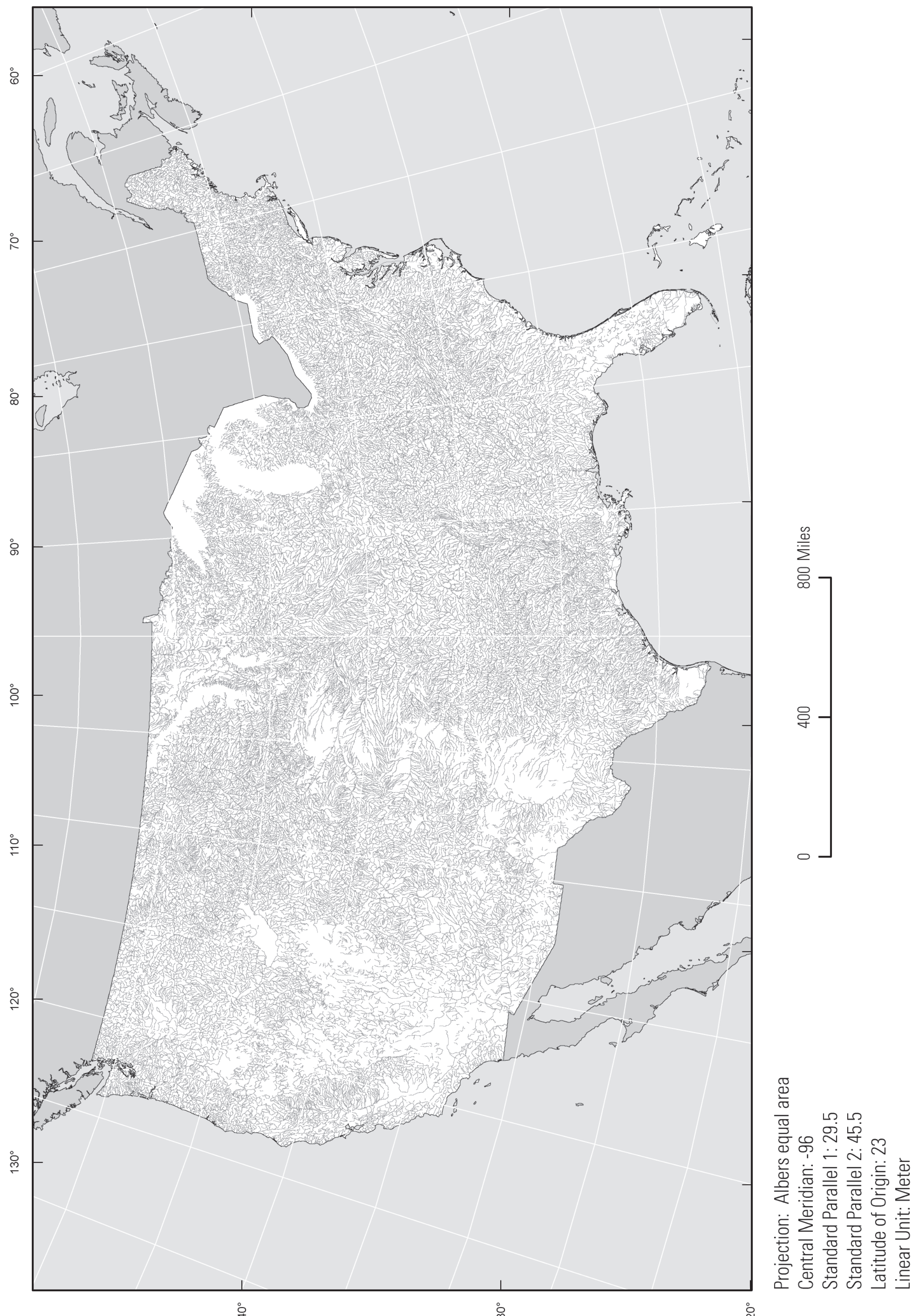

Figure 9. Density-adjusted 1:1,000,000-scale streams dataset showing less density disparity (compared to that shown in fig. 6) along adjoining boundaries of International Map of the World map sheets, continental United States.

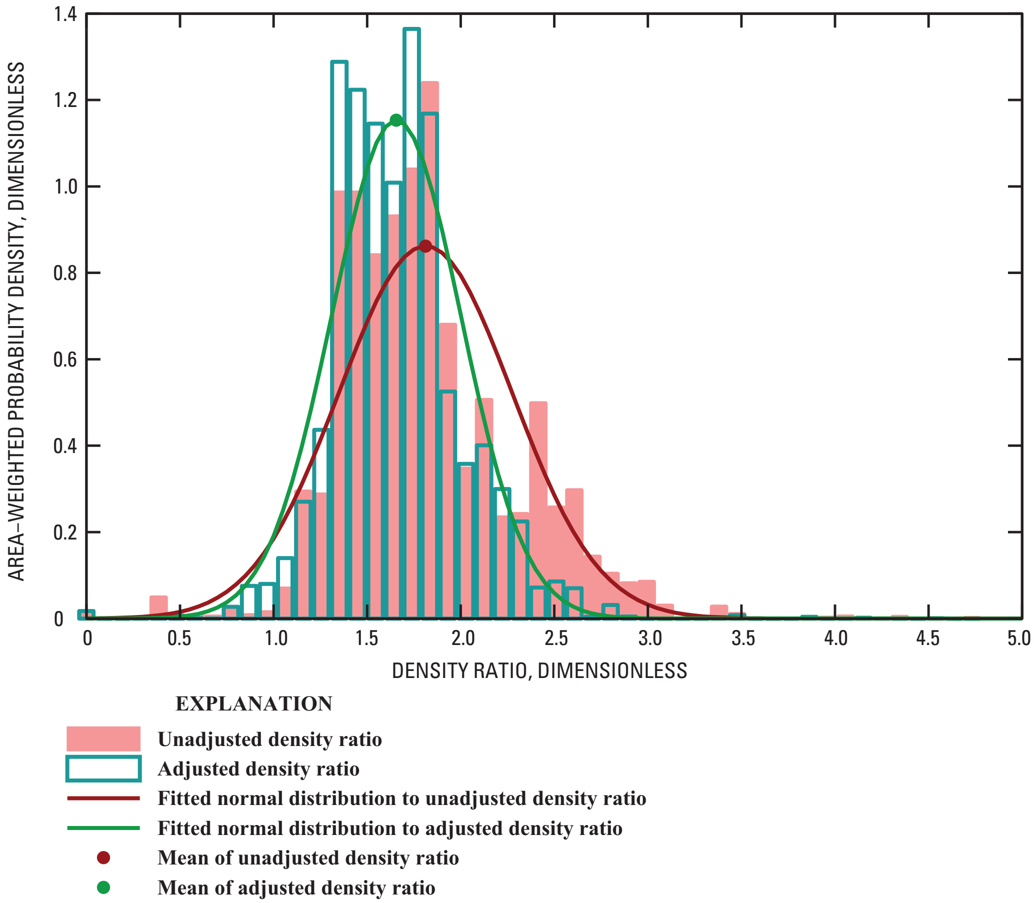

Figure 10. Area-weighted histograms and fitted normal distributions of unadjusted and adjusted stream-density ratios.

Table 3. Summary statistics of unadjusted and adjusted stream-density ratios.

[All values dimensionless]

Statistic	Unadjusted	Adjusted
Number of values	528	528
Minimum	0	0
First quartile	1.43	1.36
Median	1.77	1.62
Mean	1.82	1.64
Third quartile	2.15	1.91
Maximum	4.73	4.56
Interquartile range	.717	.550
Standard deviation	.680	.556

rescaled such that the integrals (areas) of each histogram over their domains equaled unity. Thus, both histograms and theoretical distributions share a common vertical scale for comparison purposes. The means of the unadjusted and adjusted density-ratio distributions also are shown in figure 10 as an indication of central tendency.

As the histograms in figure 10 show, the refinement procedure resulted in a slight shift of the distribution toward lower density ratios. This was expected because the procedure consisted of stream removal to enforce continuity among adjacent density polygons. However, the narrower distribution of the adjusted density ratios (as also indicated by smaller interquartile range and standard deviation [table 3]) implies that the adjustment procedure resulted in stream densities more uniformly distributed with respect to the reference 1:2M dataset.

Waterbodies

The methods used for waterbody feature selection and simplification preserve attributes and general geometry of the selected features. To refine the dataset to National

Atlas cartographic and attribute standards, feature geometry and name attributes were adjusted. NHD waterbody polygons split by quadrangle (topographic map) boundaries were merged and extended to represent the actual waterbody boundary. Name attributes that differed from National Atlas 1:2M names were verified and reconciled.

Feature Geometry Modifications

Some of the source NHD waterbody polygons were split along 1:100K and 1:24K topographic map boundaries or 1:63,360-scale topographic map boundaries for Alaska. These split polygons could have been created when the polygons were digitized from topographic maps. For example, if one topographic map showed a waterbody, but the adjacent topographic map did not show a waterbody or indicated a different name for that waterbody, the waterbody commonly was split by the map boundary. Because waterbodies often were divided into multiple parts, the feature selection process missed parts with an area less than the inclusion threshold, which caused waterbodies to have an unnatural edge created by the topographic map boundary (fig. 11). By following the topographic map boundaries laterally and vertically, the split or misaligned polygons, or both, were identified. The polygons were merged or reshaped, or both, to correlate with waterbodies shown on USGS 1:250K, 1:100K, and 1:24K digital topographic maps available as a Web Map Service (U.S. Geological Survey, 2005b).

Name Updates

Many NHD GNIS names did not match or were missing from features that were named in the National Atlas 1:2M waterbodies dataset. Polygons that intersected named National Atlas 1:2M waterbodies were examined for name consistency. The name was verified to match the name listed in the National Atlas 1:2M waterbodies dataset. If there was a discrepancy, the USGS 1:250K, 1:100K, and 1:24K topographic maps were used to verify the correct name, and the attribute was updated. Overall, 304 names were modified from the original GNIS name.

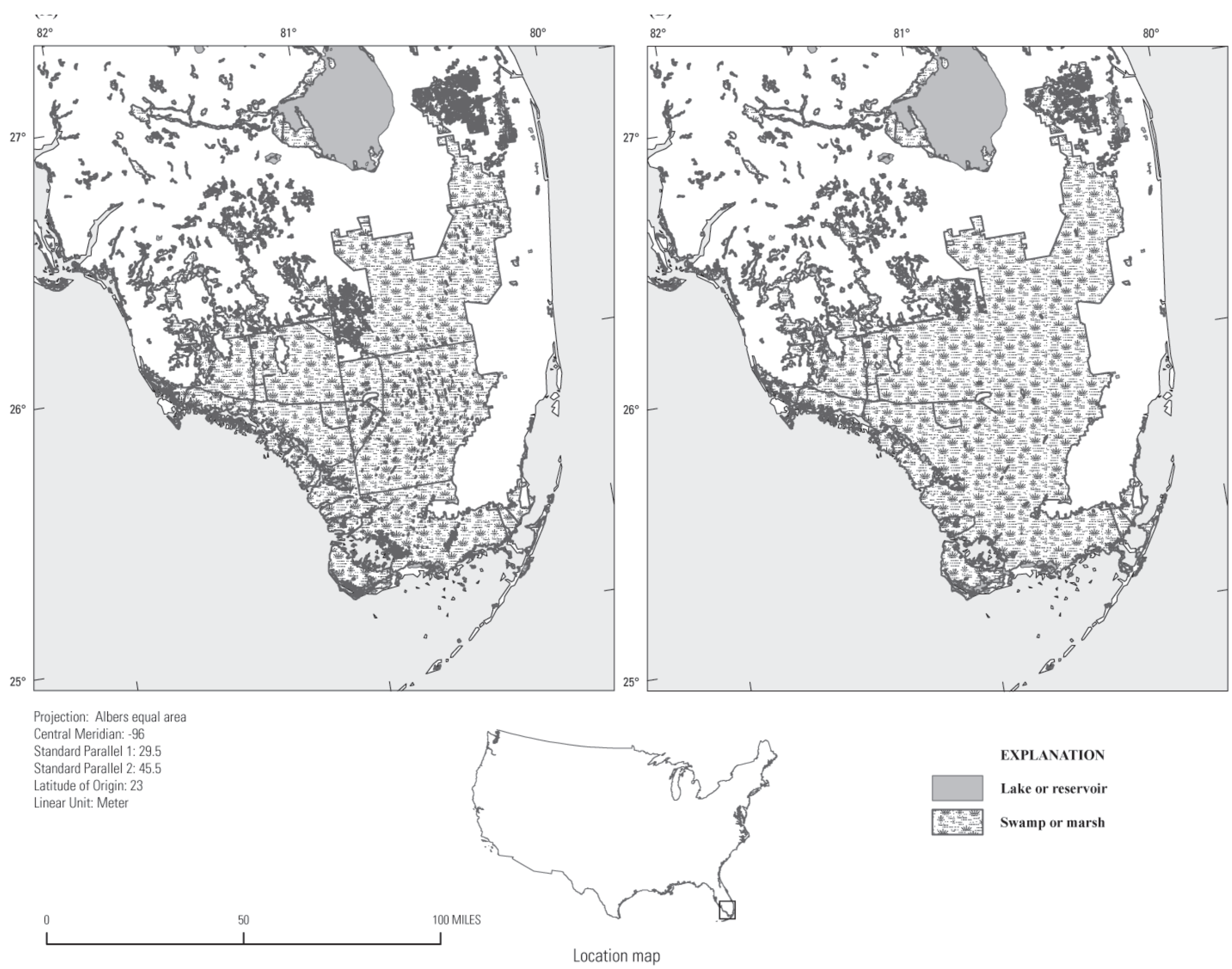

Figure 11. Example of (A) unmodified waterbodies and (B) corresponding modified waterbodies.

Summary

The development of a 1:1,000,000-scale (1:1M) nationwide hydrography dataset is critical to meeting the evolving needs of the National Atlas of the United States. During 2006–09, the U.S. Geological Survey (USGS), in cooperation with the National Atlas of the United States, produced a 1:1M hydrography dataset comprising streams and waterbodies for the entire United States, including Puerto Rico and the U.S. Virgin Islands, for inclusion in the recompiled National Atlas. The focus of this production effort was to create datasets of 1:1M streams and waterbodies, with appropriate stream density, using a method for selecting features from the USGS National Hydrography Dataset (NHD) that would be consistent across the entire United States and that also would maintain network connectivity. Additionally, the vast cartographic knowledge embedded in the National Atlas and other datasets was to be retained. This report documents the methods used to select, simplify, and refine features in the 1:100,000-scale (1:100K) (1:63,360-scale in Alaska) NHD to create the national 1:1M hydrography dataset.

Several readily available, small-scale, nationwide hydrographic datasets exist, although none of these ancillary datasets singularly fills the needs of the National Atlas recompilation effort. Primary ancillary datasets for this project included the existing National Atlas 1:2M streams and waterbodies, the Vector Map Level 0 (VMAP0), and the International Map of the World (IMW). The USGS Elevation Derivatives for National Applications (EDNA) dataset, digital orthoimagery, and digital topographic maps were used as secondary datasets.

The first step in creating the new 1:1M dataset was to address feature selection and optimal data density in the streams network. Several existing methods were evaluated: for example the ArcGIS Utility Network Analyst extension, NHD name hierarchy, hydrologic derivatives, and NHD*Plus* Thinner Codes. The production method that was established for selecting features for inclusion in the 1:1M dataset uses a combination of the existing attributes and network in the NHD and several of the concepts from the methods that were evaluated.

Headwater reaches were selected manually on the basis of whether the stream was represented in the National Atlas, VMAP0, and IMW hydrography datasets, which served as primary indicators of 1:1M stream density. The downstream trace algorithm used in this project was written in Visual Basic for Applications using ArcObjects and implemented as an easy-to-use tool within the ArcMap environment. The tool traces downstream from the selected headwater reaches and attributes reaches for inclusion in the 1:1M dataset on the basis of a set of criteria. If the tool encounters a reach that does not meet any of the selection criteria, the algorithm stops processing to allow the analyst to select the appropriate downstream reach on the basis of digital orthoimagery, georeferenced topographic maps, or the EDNA dataset. After all reaches were selected, the proposed 1:1M network was examined for connectivity.

The process for creating the 1:1M waterbodies dataset required a similar approach to that used for the 1:1M streams dataset. The NHD waterbodies are not part of a geometric network, so automating the selection process was limited to location or feature attributes, or both. The production method that was established for selecting waterbodies for inclusion in the 1:1M dataset combined a waterbody area threshold with manual verification and addition of features represented in the National Atlas 1:2M waterbodies dataset.

Geometric simplification of features, commonly done to create less complex lines for maps or to reduce data storage requirements, was the next step. Stream reaches and waterbodies indicated in the feature selection process were exported in a geographic information system as new feature classes and then simplified using the Bend Simplify algorithm of the ESRI Simplify Line tool with a tolerance of 500 meters.

The final step was refinement of the 1:1M streams and waterbodies. After selecting streams from the NHD for the 1:1M dataset, areas of stream-density disparity were apparent in the stream network when viewing the dataset at a regional scale. Because streams were selected for the 1:1M dataset partly on the basis of whether they were on an IMW map sheet, artifacts of stream-density disparity between adjacent sheets carried over to the 1:1M hydrography dataset. The stream-density disparities were visibly apparent, but to follow an objective, repeatable process, the disparities needed to be quantitatively described and identified. After the densest areas were identified, streams were removed from the 1:1M dataset to create a more uniform level of stream density. The last step in the density-adjustment process for streams was to plot all 1:1M streams for review by cartographers. Refinement of waterbodies involved fixing split waterbody polygons and name discrepancies using the 1:100K and 1:24K topographic map boundaries or 1:63,360-scale topographic map boundaries in Alaska for reference.

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Glossary

Feature class A collection of geometric representations of real-world features and their associated attributes.

Node Vertex at the end or beginning of a line segment.

Topology Refers to the spatial relation among features in a feature class, for example whether features overlap each other or have gaps between them.

Vertex (vertices [plural]) Coordinate pairs that define the shape of a line or polygon feature.

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