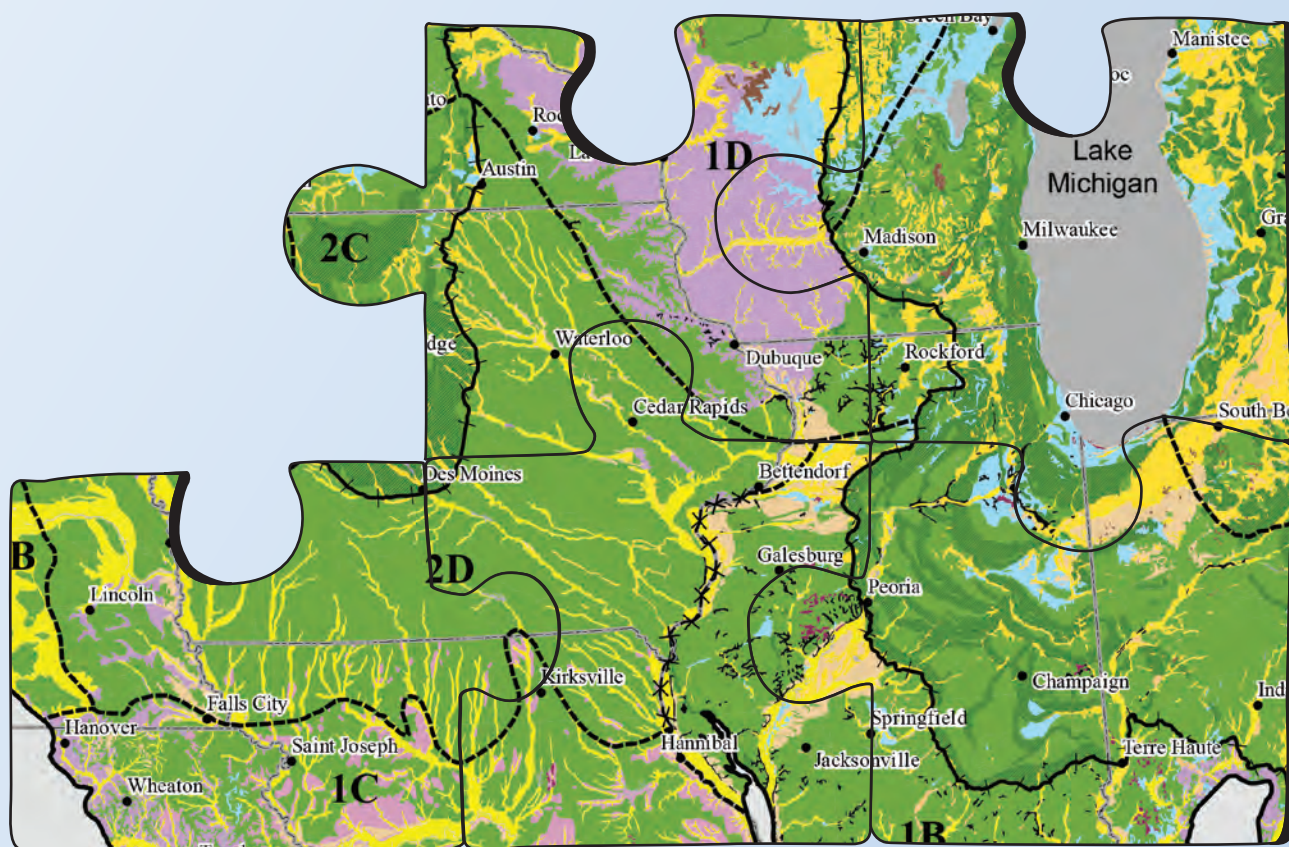


Hydrogeologic Framework for Characterization and Occurrence of Confined and Unconfined Aquifers in Quaternary Sediments in the Glaciated Conterminous United States—A Digital Map Compilation and Database



Data Series 1090

Cover. Puzzle pieces showing hydrogeologic terranes of the northern Midwest part of the map of the contiguous United States; from figure 2 of this report.

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By Adel E. Haj, David R. Soller, James E. Reddy, Leon J. Kauffman,
Richard M. Yager, and Cheryl A. Buchwald

Data Series 1090

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

U.S. Department of the Interior

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U.S. Geological Survey

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
Area		
square kilometer (km ²)	247.1	acre
square kilometer (km ²)	0.3861	square mile (mi ²)
Flow rate		
cubic meter per year (m ³ /yr)	811.03	acre-foot per year (acre-ft/yr)
cubic meter per day (m ³ /d)	264.2	gallon per day (gal/d)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

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

Supplemental Information

Per capita water use is given in cubic meters per person per day (m³ppd).

Geologic time is given in years before present (yBP).

Abbreviations

AWUDS	Aggregate Water-Use Data System
GESS	Glacial Environments and Surficial Sediments [geodatabase]
NAWQA	National Water Quality Assessment
PWS	public water system
SDWIS	Safe Drinking Water Information System
USGS	U.S. Geological Survey

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Abstract

The U.S. Geological Survey has created a hydrogeologic framework for Quaternary sediments in glaciated areas of the conterminous United States that categorizes, maps, and characterizes the glacial sediments at and beneath the land surface. The hydrogeologic framework divides the glaciated United States into 17 distinct hydrogeologic terranes using a geologic approach based on previous mapping, and was characterized using the Glacial Environments and Surficial Sediments geodatabase compiled from the Quaternary Atlas of the United States map series, the Surficial Materials Map of the United States, and several Integrated Geologic Map Databases for the United States; a groundwater use database compiled from public-supply, water-well data; and a lithologic database compiled from State-managed well records and geologic logs. This framework is to be used to assess the occurrence and characteristics of confined and unconfined glacial aquifers, their distribution and extent, and their potential intrinsic susceptibility and vulnerability.

Introduction

The U.S. Geological Survey (USGS) has completed a study to assess the occurrence and characteristics of confined and unconfined glacial aquifers in the conterminous United States, which serves as a public water supply for about 43 million people; about 60 percent of the groundwater is derived from Quaternary sediments (Yager and others, 2018b). In 2012, the USGS National Water Quality Assessment (NAWQA) program began the third decade of tracking water quality in the United States. Within the NAWQA program's scope of work is an assessment of the quality and vulnerability of groundwater in 20 principal aquifer systems that provide 75 percent of the Nation's drinking water (Rowe and others, 2013). The glacial aquifer system, defined herein as the collection of aquifers within Quaternary sediments in the glaciated

conterminous United States (fig. 1), is included as one of these principal aquifers because groundwater withdrawals from this system account for about 25 percent of the Nation's drinking water.

Figure 1. Distribution of source data from the Quaternary Atlas (Fullerton and Richmond, variously dated) and Surficial Materials Map (Soller and others, 2009) coverages used for the Glacial Environment and Surficial Sediments geodatabase for the glaciated conterminous United States. Map is available at <https://doi.org/10.3133/ds1090>.

Continuous spatial datasets with consistent description of the entire glaciated conterminous United States did not previously exist; therefore, the USGS studied and organized multiple hydrogeologic and geospatial datasets into a hydrogeologic framework for the glacial aquifer system. Maps and geospatial datasets were prepared that three dimensionally characterize the Quaternary sediments of the glaciated conterminous United States, more specifically defined as Quaternary sediment north of the line of maximum glacial advance (Booth, 2003; Soller and others, 2012). These data were intended to aid in the identification and explanation of regional patterns in aquifer occurrence, productivity, and water quality in the glacial aquifer system.

Purpose and Scope

This report describes the components of the hydrogeologic framework: the Glacial Environments and Surficial Sediments (GESS) geodatabase, which includes lithologic, geomorphic, and stratigraphic characterization of surficial and glacial sediments; hydrogeologic terranes; public-supply and domestic well databases containing groundwater use information; and a geospatial framework for visualizing and interpreting available subsurface lithologic information derived from State-managed well records and geologic logs.

Not all sediments in the study area are glacial in origin or association. For example, residual soil, bedrock outcroppings,

colluvial sediment, and mass wasting sediments are present in the study area near the limits of glaciation and where glacial sediments were eroded or not deposited. The study area also is dissected by stream valleys underlain by alluvial sediment or overlain by eolian sediment (sand and loess). In some of these cases, sediments are not associated with glaciation; moreover, sediments may not be Quaternary in age, but may be important hydrologically, and so were included in the scope of this report.

Hydrogeologic Framework

Multiple hydrogeologic and geospatial datasets were organized into the hydrogeologic framework for the glacial aquifer system. The components of the hydrogeologic framework are described in this section, including the GESS geodatabase, hydrogeologic terranes, public-supply and domestic well databases containing groundwater use information; and well log database derivatives of the geospatial framework for visualizing and interpreting available subsurface lithologic information derived from State-managed well records and geologic logs.

Approach

Surficial and bedrock geologies, to a large extent, control the occurrence and geometry of aquifers and the likelihood that they might provide a useable supply of groundwater. Predictability of geology is especially difficult for terrestrial depositional settings such as glaciated areas, given the nature of glaciofluvial processes and the numerous glaciations to which large areas of the United States have been subjected. At the land surface these sediments may be well understood and mapped but, in the subsurface, they generally are poorly understood, at least to the level of detail sufficient to delineate individual aquifers. The reasons for this include the high cost of obtaining subsurface information and difficulties in predicting the geometry and variations in lithology of buried aquifers. The scale at which the hydrogeology can be characterized is limited by the scale at which geologic sediments have been mapped. This study has adopted a generalized approach to characterizing and classifying the glacial geologic framework of the United States, taking into account the regional character of surficial and bedrock geology, to provide a tool for describing the Nation's aquifers within the glacial aquifer system, and the potential vulnerability to contamination of these aquifers at depth.

The Glacial Environments and Surficial Sediments Geodatabase

Two previous studies that produced maps and geodatabases characterizing surficial sediments at the national scale were used to create the GESS geodatabase, a geospatial

database that categorizes, maps, and characterizes the physical properties of the glacial sediments. The first and primary source was the Quaternary Atlas of the United States map series (Fullerton and Richmond, variously dated). Geodatabases from Fullerton and Richmond (variously dated), a 1:1,000,000-scale $4^{\circ} \times 6^{\circ}$ quadrangle map series, were downloaded and merged into a single geodatabase (referred to herein as the "Quaternary Atlas") for the glaciated conterminous United States. The selected quadrangle maps used to create the Quaternary Atlas and the coverage extent of the study area are shown in figure 1. The 1:5,000,000-scale "Map Database for Surficial Materials in the Conterminous United States" (Soller and others, 2009; referred to herein as the "Surficial Materials Map") was used as a secondary data source, filling in the gap in the Quaternary Atlas coverage in the northwestern United States (fig. 1).

Although the Quaternary Atlas lacked full coverage of the study area, it was selected as the cornerstone for the GESS geodatabase because of the higher resolution (1:1,000,000-scale compared with the Surficial Materials Map database at 1:5,000,000-scale). The Quaternary Atlas also had more mapped spatial elements (that is, polygons), about 800,000 (compared with the Surficial Materials Map, which had 9,555 spatial elements) with detailed sedimentological, geomorphological, and geological attributes derived from State and Canadian Provincial geological surveys, universities, the Geological Survey of Canada, the USGS, and private industry. Although the Surficial Materials Map was not primarily used to derive new GESS geodatabase attributes in the Quaternary Atlas coverage area, it is a geodatabase with consistent and verified descriptions and extents of surficial sediments in the study area; therefore, all its spatial elements and attributes were retained in the GESS geodatabase for reference and comparison purposes.

Study Area Discretization

The study area was discretized for the GESS geodatabase using spatial elements from the Quaternary Atlas, modified slightly to fill gaps at quadrangle boundaries and extended inlets along the eastern U.S. coastline. Where the Quaternary Atlas lacked coverage in the northwest, spatial elements from the Surficial Materials Map were used. New attributes for the combined framework were derived for this study from the Quaternary Atlas and the Surficial Materials Map maps and databases that describe aspects of the depositional environment, texture and character, and geomorphic expression of the surficial sediments and may affect the hydrogeologic properties of the sediments. These GESS geodatabase attributes are described below.

Map Unit

The GESS geodatabase map unit (attribute GESS_MU) values were designated using Quaternary Atlas map unit descriptions (attribute N_MAPUNITS) and geologic

description codes (or geocodes; attribute GEOCODE; Fullerton and Richmond, variously dated); terminology and geocode abbreviations were defined by Fullerton and others (2003). The Quaternary Atlas map series is the culmination of the efforts of numerous scientists over decades, and thus contained inconsistencies in use of terminology, outdated terms, incomplete descriptions, or a combination of these inconsistencies. Fullerton and others (2003) standardized the terminology used for each Quaternary Atlas quadrangle map, but some variability still exists. Variability and inconsistencies in lithologic descriptive terminology also exists among the quadrangles maps. For assignment of GESS_MU attribute values, identical Quaternary Atlas map unit descriptions were grouped, and then those groups were combined into categories based upon similarity in map unit descriptions and using

the classification system of Fullerton and others (2003). The resultant 14 Quaternary Atlas map unit categories were translated to GESS geodatabase map unit values: alluvial sediment, bedrock, colluvial sediment, eolian sediment, fill, ice-contact sediment, lacustrine sediment, marine sediment, organic sediment, outwash sediment, residual soil, solifluction sediment, till, and water (table 1). Where insufficient information in the lithologic description was present in the Quaternary Atlas map unit attribute, the geocode attribute was used to set the value for the GESS geodatabase map unit such that every spatial element in the GESS geodatabase possessed a map unit value. In the part of the study area with no coverage in the Quaternary Atlas, unit names for the spatial elements from the Surficial Materials Map were correlated to the 14 GESS geodatabase map unit values (table 1).

Table 1. Classification of map units in the Glacial Environment and Surficial Sediments geodatabase classification and corresponding map unit values from the Quaternary Atlas and the Surficial Materials Map.

[The Quaternary Atlas is from Fullerton and Richmond (variously dated); the Surficial Materials Map is from Soller and others (2009). GESS_MU, map unit attribute in the Glacial Environment and Surficial Sediments (GESS) geodatabase; N_MAPUNITS, Quaternary Atlas map unit attribute; GEOCODE, Quaternary Atlas attribute for geological classification; NA, not applicable]

GESS_MU	Attribute value from Quaternary Atlas		Map unit value from Surficial Materials Map
	N_MAPUNITS	GEOCODE ¹	
Alluvial sediment	All subcategories of alluvial, alluvium, and sheetwash sediments	al, a, ² a, ³ ggk, wlc, wla	All subcategories of alluvial sediments.
Bedrock	Bedrock and dissected bedrock	qs, R, Rb	Volcanic rocks, basaltic and andesitic.
Colluvial sediment	All subcategories of colluvium and landslide deposits	c, ² c, ³ j ³	Colluvial sediments; colluvial sediments and alluvial sediments or residual material.
Eolian sediment	All subcategories of eolian, loess, beach and dune sand	e, ² e, ³ be	All subcategories of eolian sediments.
Fill	Manmade fill, and manmade land	f	NA
Ice-contact sediments	All subcategories of ice-contact and kame	k, ² k ³	All subcategories of glaciofluvial ice-contact sediments, mostly sand and gravel.
Lacustrine sediment	All subcategories of lake sediments	la, lc, ² ld, ² lg, ² ll, ² ls ⁴	All subcategories of proglacial sediments, mostly fine grained.
Marine sediment	All subcategories of marine deposits	m, ² m ³	All subcategories of coastal zone sediments.
Organic sediment	All subcategories of peat, muck, swamp and marsh deposits	h, ² h ³	All subcategories of organic-rich muck and peat.
Outwash sediment	All subcategories of outwash sediments	gg, ⁵ g, ² g, ³ lsb	All subcategories of proglacial sediments, mostly coarse grained.
Residual soil	All subcategories of solution, decomposition, and disintegration residuum, and glaciated granitic grus	asm, rc, ² xc, ² xl, ² xs, ² zl, ² zr, ² zs, ² ugg	All subcategories of residual materials.
Solifluction sediment	All subcategories of soliflucted deposits	nla, nlb, nlc, ⁶ nld, nma	NA
Till	All subcategories of till, ice-thrust, and solifluction deposits and till	t, ³ t, ² IT, nlc ⁷	Glacial till sediments.
Water	Water	Water	Water.

¹An index for geocode abbreviations, definitions, and explanations of terms can be found in Fullerton and others (2003).

²Include single prefix or single suffix characters combinations.

³Include double prefix or double suffix characters combinations.

⁴All subcategories of ls except for lsb.

⁵Includes all gg and single suffix characters combinations except ggk.

⁶Except when description includes till.

⁷Only when description includes till.

Not all GESS geodatabase map units represent Quaternary sediments of glacial origin. Colluvial sediment, residual soil, and solifluction sediment GESS geodatabase map units are generally areas with thin or no glacial sediment, where sediment tends to be of greater geologic age, or is present on upland or steeply sloped surfaces. In all these cases, the likelihood of a glacial aquifer existing in these areas is very low and, therefore, fall outside the scope of this study. For similar reasons, bedrock, fill, and water GESS geodatabase map units also were disregarded, leaving the focus of this study on areas with the remaining eight GESS geodatabase map unit values: alluvial sediment, eolian sediment, ice-contact sediment, lacustrine sediment, marine sediment, organic sediment, outwash sediment, and till (fig. 2; table 2).

Figure 2. Glacial Environment and Surficial Sediments (GESS) geodatabase map units (GESS_MU attribute) in the glaciated conterminous United States. Map is available at <https://doi.org/10.3133/ds1090>.

Geomorphic Modifier

The hydrogeologic properties of many glacial sediments may be affected by their geomorphology and depositional environment. This is particularly true for glacial till. As a result, the attribute “GESS_Modifier” was created for each spatial element and given a value of “e” (end moraine), “g” (ground moraine), “s” (stagnation moraine), “d”

(discontinuous or attenuated), or “f” (solifluction sediment) primarily for those spatial elements with GESS geodatabase map unit values of “till” (table 2). All GESS_Modifier values for those units were set to “g,” unless information was present in the lithologic descriptions, geocodes, or other attributes in the Quaternary Atlas and the Surficial Materials Map to assign an alternative value. Other spatial elements may have GESS_Modifier values because of potential importance in future hydrogeologic applications of this database (table 2).

Stratified Compared to Unstratified Sediments

The StratSed attribute was created to identify the extent of sediments that have been transported by wind or water before deposition; these sediments were considered “stratified.” Aquifers are typically composed of coarse-grained, stratified glacial sediments, such as kame sands, outwash gravels, or eolian sand, whereas the unstratified sediments, primarily till, generally are less productive or are confining units. All spatial elements with GESS_MU values of alluvial sediment, eolian sediment, ice-contact sediment, lacustrine sediment, marine sediment, and outwash sediment were identified as stratified sediments, and the StratSed attribute value was set to “1;” the remaining spatial elements with a GESS_MU attribute value of organic sediment (including precluded GESS geodatabase map units residual soil and solifluction sediment) and till were classified as unstratified, and the StratSed attribute value was set to “0” (table 2).

Table 2. Subcategories for map units for Quaternary sediments in the Glacial Environment and Surficial Sediments geodatabase.

[GESS, Glacial Environment and Surficial Sediments geodatabase; GESS_MU, GESS map unit attribute; StratSed, GESS attribute for stratified sediment; CrseStratSed, GESS attribute for coarse, stratified sediments; Texture6, GESS attribute that classifies texture; GESS_Modifier, GESS attribute imparting additional details for the spatial element; NA, no data available; d, discontinuous; e, end moraine; f, solifluction sediment; g, ground moraine; s, stagnation moraine]

GESS_MU	StratSed ¹	CrseStratSed ²	Texture6	GESS_Modifier
Alluvial	1	1	Mostly sandy and sandy-silty	NA
		0	Mostly silty ³ and silty-clayey ³	
Eolian	1	1	Mostly sandy	NA
		0	Sandy-silty	
Ice-contact	1	1	Mostly sandy	NA
Lacustrine	1	1	Mostly sandy ³ and sandy-silty ³	NA, d
		0	Silty-clayey and mostly clayey	
Marine	1	1	Mostly sandy	NA, d
		0	Silty-clayey	
Organic	0	0	Mostly organic	NA
Outwash	1	1	Mostly sandy	NA
Till	0	0	Mostly sandy, sandy-silty, mostly silty, silty-clayey, and mostly clayey	d, e, f, g, s

¹A value of 1 indicates stratified, and 0 indicates unstratified sediments.
²A value of 1 indicates coarse, stratified sediments, and 0 indicates unstratified sediments or fine, stratified sediments.
³Few spatial elements with this value and associated GESS_MU.

Textural Classification

A six-bin classification system for sediment texture was created for all the spatial elements of the GESS geodatabase, attribute “Texture6.” The Quaternary Atlas textural descriptions were grouped, simplified, and categorized into six categories: mostly sandy, sandy-silty, mostly silty, silty-clayey, mostly clayey, and mostly organic. This classification scheme allowed for investigation of the potential hydrogeologic effects of sediment texture in the Quaternary Atlas while remaining compatible with the more generalized, four-bin textural classification system used by the Surficial Materials Map (table 3). Although the terminology and the generalizing of textural attributes used in the Surficial Materials Map is similar to the terminology and generalization in the GESS geodatabase, it should be noted that some discrepancies may exist between the Quaternary Atlas descriptions, the Surficial Materials Map textural classes, and textural values in the GESS geodatabase. An example of this can be seen in table 3, where the GESS geodatabase Texture6 value “mostly silty” derived from Surficial Materials Map spatial elements would be correlative with spatial elements derived from the Quaternary Atlas with “sandy-silty,” “mostly silty,” and “silty-clayey” values. The values are intended to be qualitative descriptions of relative sediment textures for till (unstratified) and stratified sediments independently; for example, “mostly sandy” till is coarser in texture than “silty-clayey” till but would not have the same

particle-size distribution as “mostly sandy” outwash sediment. The extent of the GESS geodatabase textural classes are displayed in figure 3.

Figure 3. Textural classification of Glacial Environment and Surficial Sediments geodatabase map units in the glaciated conterminous United States. Map is available at <https://doi.org/10.3133/ds1090>.

Bedrock Lithology and Coarse-Grained, Stratified Sediments

Groundwater interaction between aquifers in glacial sediments and the underlying bedrock may have important implications when comparing water-quality data from the glacial aquifer system in a hydrogeologic framework; for example, groundwater exchange with carbonate bedrock aquifers may affect the buffering capacity of the overlying glacial aquifers. To better anticipate where these interactions might be present and potentially affect water quality, a bedrock geology map was overlain by GESS geodatabase spatial elements possessing coarse, stratified glacial sediments. The GESS geodatabase attribute for coarse, stratified sediments (attribute CrseStratSed) was created and assigned a value of “1” for spatial elements with a StratSed attribute value of “1” and Texture6

Table 3. Textural classification from the Glacial Environment and Surficial Sediments geodatabase (this report) compared with textural descriptions of sediments from the Quaternary Atlas and the Surficial Materials Map.

[Glacial Environment and Surficial Sediments (GESS) geodatabase is from this report; the Quaternary Atlas is from Fullerton and Richmond (variously dated); and the Surficial Materials Map is from Soller and others (2009). Texture6, GESS attribute that classifies texture in one of six values; Texture4, GESS attribute that classifies texture in one of four values; GESS_MU, GESS map unit attribute; GEOCODE, Quaternary Atlas attribute for geological classification]

Texture6	Quaternary Atlas description of sediment texture		Surficial Materials Map description of sediment texture (Texture4)
	Till	Stratified sediment	
Mostly sandy	Sandy; silt, sand and gravel ¹	Sand; sandy; sand and gravel; gravel; sandy to silty; silt and sand ^{2,3} ; silt, sand, and gravel; clay, silt, sand and gravel ² ; silty clayey sand; silty clay, sand and gravel	Mostly sandy.
Sandy-silty	Sandy to clayey ⁴ ; sandy loamy; loamy or sandy	Sandy and loamy; sandy loamy; sandy silty; silt and sand	Mostly silty.
Mostly silty	Loamy; clayey to sandy ⁴ ; sandy to clayey ⁴	Silt	
Silty-clayey	Loamy and clayey; clay loam; clayey to loamy	Clay and silt; clay, silt and sand; loamy and clayey; silty clayey; clay, silt, sand and gravel ⁵	
Mostly clayey	Clayey	Clay	Mostly clayey.
Mostly organic	All subcategories of peat, muck, swamp, and marsh deposits; concordant with GESS_MU attribute value = organic sediments		Mostly organic.

¹Applies to spatial elements described as ice thrust deposits.

²Applies to spatial elements with GESS_MU value of alluvial only.

³Applies to spatial elements with GESS_MU value of eolian only.

⁴Variable texture in description, further information gathered from GEOCODE to determine Texture6 value.

⁵Applies to spatial elements with GESS_MU value of lacustrine only.

attribute value of “mostly sandy” and “sandy silty” (table 2; fig. 4).

Figure 4. Generalized bedrock lithology (modified from the Integrated Geologic Map Databases for the United States) and overlying Glacial Environment and Surficial Sediments geodatabase coarse-grained, stratified sediments in the glaciated conterminous United States. Map is available at <https://doi.org/10.3133/ds1090>.

The bedrock geology for the GESS geodatabase is an amalgamation of several “Integrated Geologic Map Databases for the United States” (Dickens and others, 2005; Ludington and others, 2007; Nicholson and others, 2007a–c; Stoesser and others, 2007). Using the LITH62 and LITH62MINO attribute values from that integrated geologic map databases and the associated lithclass 6.2 code text descriptions, spatial

elements of the integrated geologic map databases were grouped and compared to GESS geodatabase spatial elements. A new GESS geodatabase attribute was created, named “Litho_class,” and each GESS geodatabase spatial element was given a Litho_class value of noncarbonate sedimentary rock, carbonate rock, noncarbonate metamorphic rock, volcanic rock, plutonic rock, or undetermined (areas where bedrock lithology was not mapped in the integrated geologic map databases).

Some Litho_class values were further modified from the above classification scheme. Areas described as “mélange” were assigned Litho_class attribute values of “noncarbonate metamorphic rock;” those described as “dams” were assigned values of “unconsolidated;” and those described as “RI (Rhode Island) coastals” were assigned a value of “plutonic.” In the Midwestern United States, some areas classified as unconsolidated materials (LITH62 values) when cross-referenced with

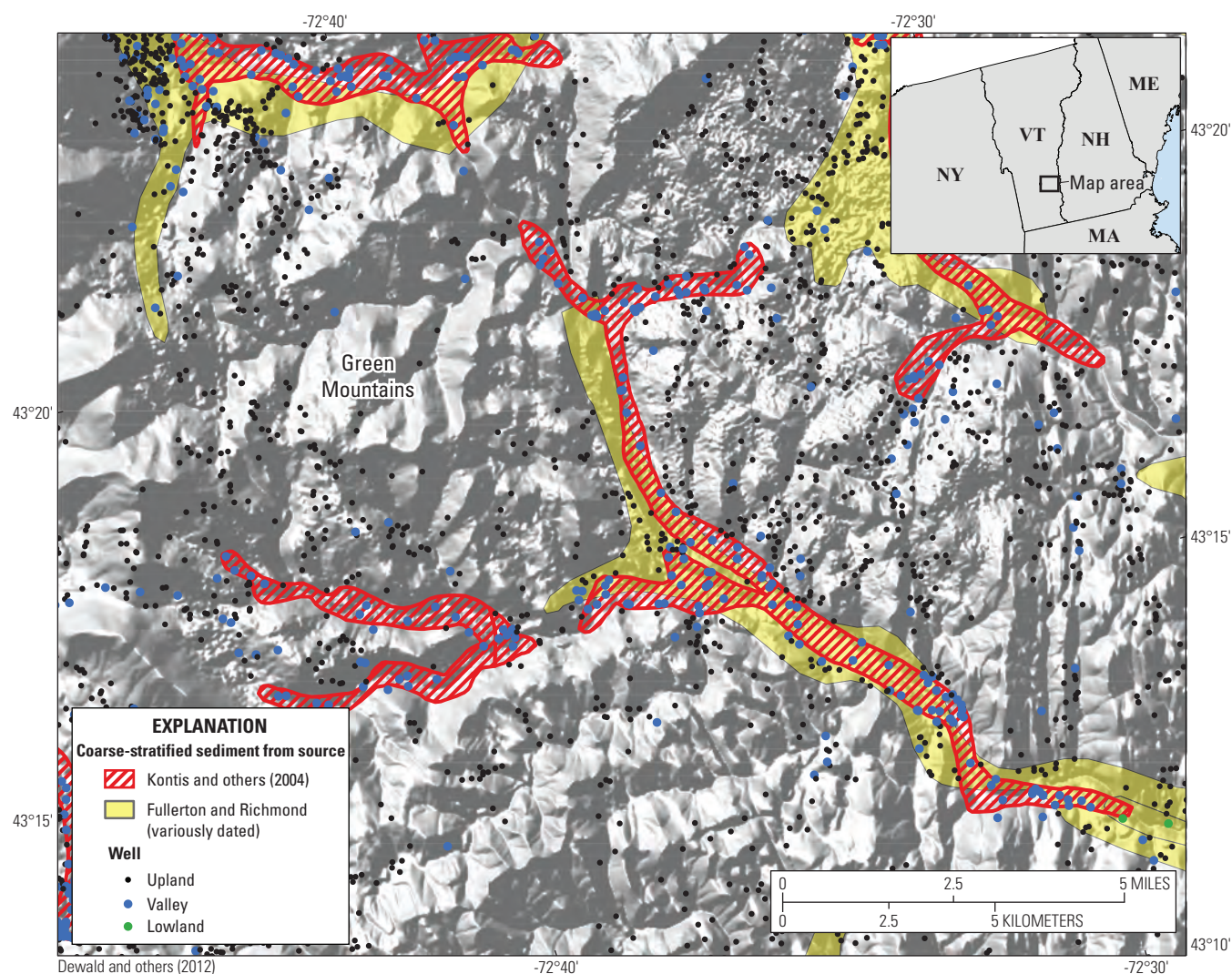


Figure 5. Comparison of extent of coarse-stratified sediment from Kontis and others (2004) and the Glacial Environment and Surficial Sediments geodatabase (Fullerton and Richmond, variously dated), southeastern Vermont.

the Database of the Geologic Map of North America (Garrity and Soller, 2009) were underlain by sedimentary rocks. Spatial elements in these areas with Litho_class attribute values of “unconsolidated” were changed to “noncarbonate sedimentary rock.” Spatial elements with Litho_class attribute values of “unconsolidated” that did not fall within the Midwestern United States were changed to “undetermined.”

Interpretations and Applications

A few inherent qualities of the GESS geodatabase should be considered when interpreting or applying GESS geodatabase attributes and values in a hydrogeologic context. Foremost of these considerations is the scale of the datasets gathered for this investigation and the scale of the aquifer in which the reader may have an interest. The GESS geodatabase was

compiled from the Quaternary Atlas and the Surficial Materials Map databases. The Quaternary Atlas was selected as the primary source of geospatial information because of the richness of map units and lithologic data. The 1:1,000,000 scale of the Quaternary Atlas is well-suited for this study and other studies at the national or regional scale; however, if the aquifer in question is set in a geologic unit or surficial sediment deposit having an extent smaller than can be delineated at that scale, that aquifer may not be discretized in the GESS geodatabase. Examples of this can be seen in two areas of the northeastern United States (figs. 5 and 6). In both of these areas, wells in coarse-grained, stratified drift (blue) delineate an aquifer that is not adequately mapped in the GESS geodatabase at the 1:1,000,000 scale. In this region of the country, another dataset is available, which has mapped stratified aquifers in glacial sediments at a more detailed scale (Kontis

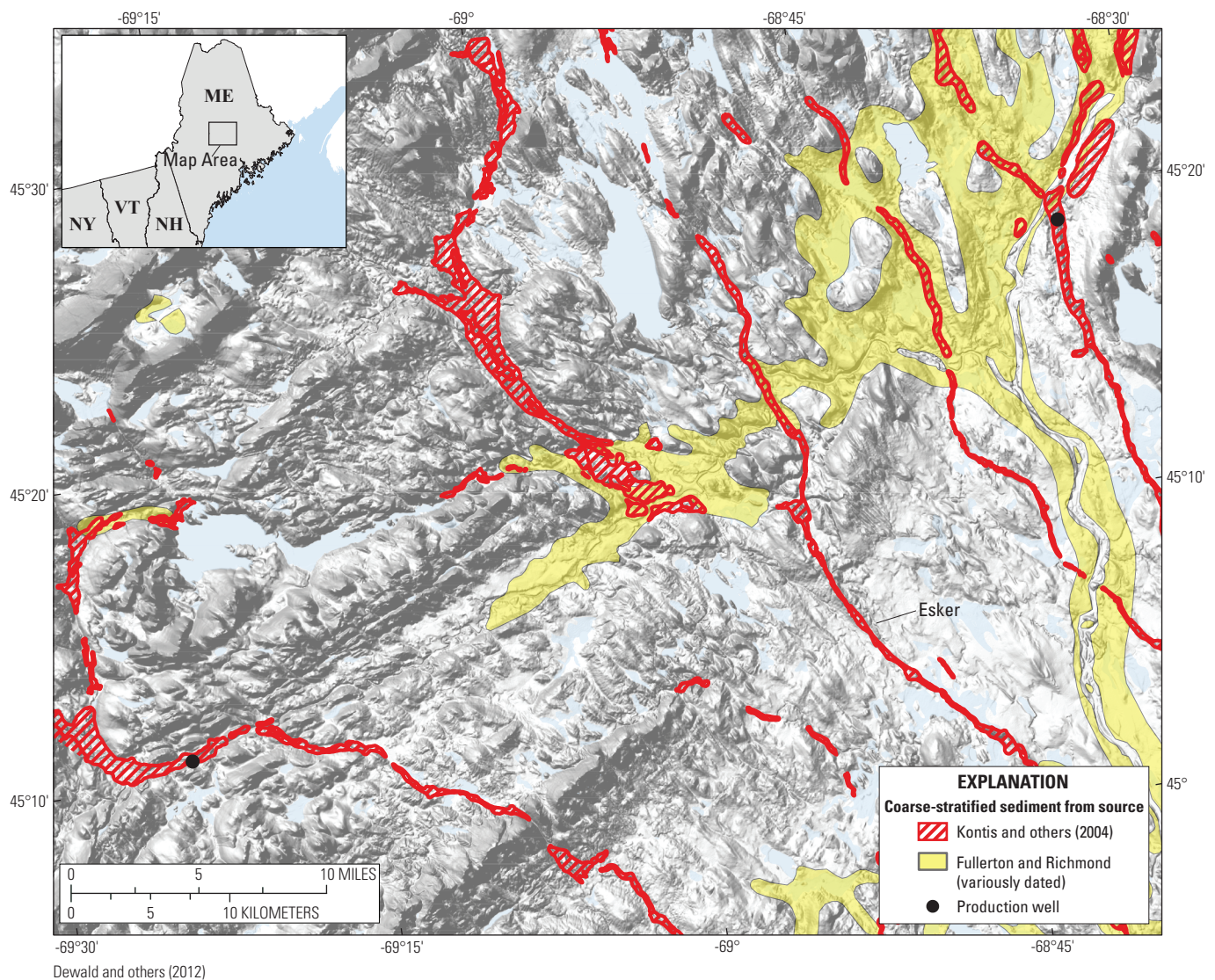


Figure 6. Comparison of extent of coarse-stratified sediment from Kontis and others (2004) and the Glacial Environment and Surficial Sediments geodatabase (Fullerton and Richmond, variously dated), central Maine.

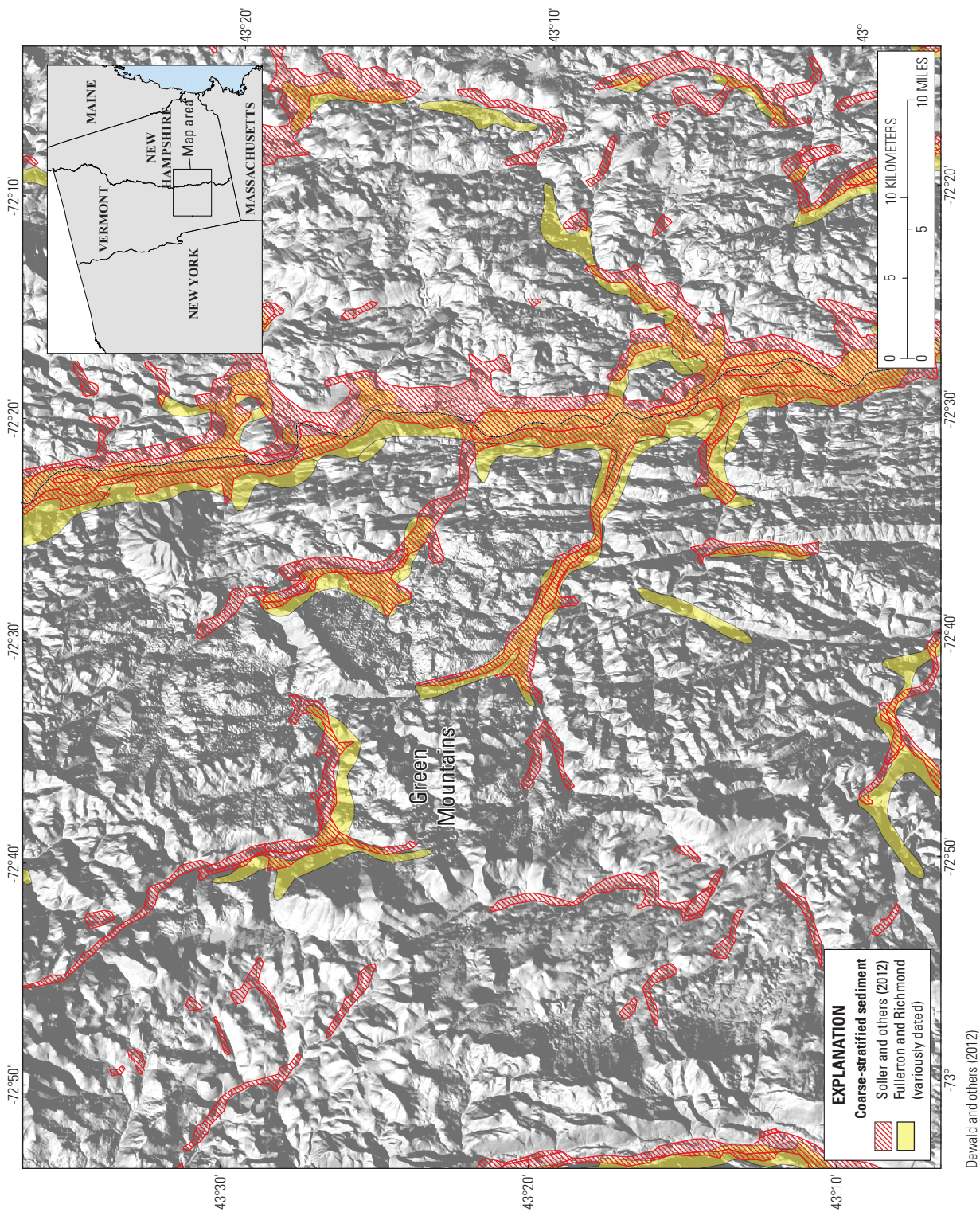


Figure 7. Comparison of extent of coarse-stratified sediment from Kontis and others (2004) and the Glacial Environment and Surficial Sediments geodatabase (Fullerton and Richmond, variously dated), southern Vermont and New Hampshire.

and others, 2004). A modified version of the Kontis and others (2004) database is included in this study—adjustments were made along State boundaries and topographic corrections were added (P. Heisig, USGS, oral commun., 2017). The modified Kontis and others (2004) database, shown in figures 5 and 6, shows a mapped area of coarse-grained, stratified sediments that includes the wells, and so likely is better suited for interpretation of groundwater data in glaciated mountainous areas where the size of aquifers generally is smaller than can be shown at 1:1,000,000 scale.

A second consideration when applying the GESS geodatabase is the existence of discontinuities in mapped features and lithological information at State and Quaternary Atlas $4^{\circ} \times 6^{\circ}$ quadrangle map boundaries. The Quaternary Atlas is a compilation of individual $4^{\circ} \times 6^{\circ}$ quadrangle maps, assembled by different researchers over many years from various databases, which have created data anomalies and discontinuities among the map units shown on the various quadrangles and in attribute values (geocodes, lithologic description, and so on). Two of the more apparent examples of this can be seen in the northeastern United States at the NL-19 Quebec and NK-19 Boston quadrangle boundary and at the New Hampshire-Massachusetts State boundary, although more subtle anomalies exist in the GESS geodatabase elsewhere (figs. 1 and 2).

Lastly, there may be spatial discrepancies with map spatial elements in the GESS geodatabase and other available geospatial datasets. In some instances, GESS geodatabase map units may appear offset from features from other spatially referenced data. Although these offsets may seem slight in some areas, in other areas the offset must be considered when comparing well data to mapped features in the GESS geodatabase. In figures 5 and 6, the coarse-grained, stratified sediments of the GESS geodatabase, shown in yellow, coincide for the most part with the wells identified as “valley” wells and with low topographic areas; however, in some areas, coarse-grained, stratified sediments are mapped on the upland surface and incorporate “upland” wells. This discrepancy may produce inaccuracies in the interpretation of well data within the area.

Other smaller-scale datasets exist that may supplement the GESS geodatabase and decrease inaccuracies in application of and interpretations from map unit coverage. In this example, using the modified version of the stratified drift aquifers (Kontis and others, 2004) in an analysis of these aquifers may be more appropriate and yield better interpretive results; the coarse-grained, stratified sediments (modified from Kontis and others, 2004) in figures 5 and 6 are more inclusive of “valley” wells. This comparison is discussed further in Yager and others (2018b).

Other hydrologically significant datasets exist at a scale similar to the GESS geodatabase that can be used to supplement interpretive investigations. Soller and others (2012) mapped coarse-grained, stratified sediments in the United States east of the Rocky Mountains at a 1:1,000,000 scale. The map units in this database were derived from a different map compilation than those used in the GESS geodatabase and, in some parts of the study area, the occurrence of coarse-grained,

stratified sediments and other map units may differ. An example of this can be seen in figure 7. A comparison of data from the GESS geodatabase, Soller and others (2012), and the underlying digital elevation model (DEM; Dewald and others, 2012) indicates that, in some areas, mapped units for coarse-grained, stratified sediments in the GESS geodatabase and Soller and others (2012) are more or less coincident, whereas in other areas they are offset yet overlap or they are isolated from one another. Moreover, the comparison of coarse-grained, stratified sediments (of both the GESS geodatabase and Soller and others [2012]) and the valley bottoms as shown in the DEM indicate some discrepancies. Because of these inherent qualities in the GESS geodatabase and in other geospatial databases and maps, caution must be exercised when using the GESS geodatabase to interpret hydrogeologic conditions and aquifer characteristics at a particular well site or at a small scale. The GESS geodatabase was constructed to use the richest geospatial datasets to investigate hydrogeologic trends in aquifers in glacial sediments within broad regions of the United States and at the national scale, but the aforementioned limitations must be recognized.

Hydrogeologic Terranes

For the glaciated area of the United States, this study used existing maps and knowledge of the regional geology as the basis for a generalized hydrogeologic classification of glacial sediments (Soller and others, 2009, 2012; Soller and Garrity, 2018). This classification was designed to address the potential for encountering coarse-grained sediments (for example, sand and gravel) that may serve as aquifers. Given the emphasis, various regions were delineated, termed “hydrogeologic terranes,” and defined using four criteria: overall thickness of Quaternary sediments, with the assumption that greater thickness was associated with a higher likelihood of encountering aquifers in the subsurface; the predominant modes of glacial deposition (for example, ice advance that was mostly unconstrained by other glacial lobes, intermoraine regions between major ice lobes, and so forth); the predominant texture of the surficial sediments; and the geologic age of the sediments, such that sediments of the latest glaciation, Late Wisconsinan, may differ from older glacial sediments in terms of their weathering characteristics and, in turn, hydrogeologic characteristics.

Hydrogeologic Terrane Classification

The first of those criteria, overall thickness of Quaternary sediments, was used to infer, delineate, and qualitatively rank hydrogeologic complexity that may exist in each terrane. These rankings are highly generalized, used only to give a sense of the relative potential for encountering buried aquifers. Regions with a thin cover (generally less than 15 meters [m]) of Quaternary sediments were assigned a value of “lower” complexity (terrane code 1); regions with thick sediment

cover (generally greater than 60 m) were assigned a value of “higher” complexity (terrane code 3); regions with a moderate thickness (between 15 and 60 m, but generally 30 to 40 m) were assigned a value of “moderate” complexity (terrane code 2). Two areas of moderate to thick sediment cover were assigned a value (terrane code 4). These areas have unique glacial settings, described in more detail in the “Hydrologic Terranes with Thick, Coarse-Grained, Stratified Quaternary Sediments” section. The correspondence of Quaternary sediment thickness and the hydrogeologic terrane boundaries are shown in figure 8 (Soller and others, 2012).

Figure 8. Hydrogeologic terranes and the thickness and character of glacial sediments in the glaciated conterminous United States. Map is available at <https://doi.org/10.3133/ds1090>.

Terranes of similar complexity were then evaluated based upon the remaining criteria: mode of deposition, texture, and geologic age. Letter designations were appended to the numeric codes for complexity (for example, 1A, 3C); these denote differences among terranes ranked with similar complexity, and their correspondence to the hydrogeologic terrane boundaries is best illustrated in figure 9.

Figure 9. Hydrogeologic terranes and the maximum glacial advance of the glaciated conterminous United States. Map is available at <https://doi.org/10.3133/ds1090>.

Hydrogeologic Terrane Description

According to the four classification criteria, Quaternary sediments (including sediments of glacial and nonglacial origin) within the glaciated area of the conterminous United States were classified into 17 hydrogeologic terranes (fig. 10). The terranes are grouped by complexity, and their hydrogeologic characteristics are summarized below. More information about the geologic and aquifer characteristics of the terranes and accompanying data sets can be found in Yager and others (2018a,b). Definitions and explanations of terms used in this section is provided in Fullerton and others (2003).

Figure 10. Glacial features, by hydrogeologic terrane, in the glaciated conterminous United States. *A*, terranes 1A and 4A in the northeastern United States; *B*, terranes 1B, 2A, and 3A in western Ohio, Michigan, Indiana, Illinois, eastern Wisconsin, and a small area of northern Kentucky; *C*, terranes 1C, 2C, 2D, 3C, and 4B in Iowa, southern Minnesota, southeastern South Dakota, northern Missouri, eastern Nebraska and Kansas, and a small area of western Illinois; *D*, terranes 1D, 1E, 2B, and 3B in Minnesota, Wisconsin, upper Michigan, northern Illinois, and eastern North and South Dakota; *E*, terranes 1F and 2E in North and South Dakota and in eastern Montana; and *F*, terrane 1G in Washington, Idaho, and western Montana. Maps are available at <https://doi.org/10.3133/ds1090>.

Hydrogeologic Terranes of Lower Complexity

The following terranes are of lower complexity with a thin (generally less than 15 m) cover of Quaternary sediments.

Terrane 1A—Predominantly Late Wisconsinan Sediments in Eastern Ohio Through New England

Hydrogeologic terrane 1A consists of mostly thin Quaternary sediments and exposed bedrock (mixed sedimentary rocks and igneous and metamorphic rocks). The physiography of this broad area, east of the Appalachian Escarpment in Ohio, varies considerably and includes high relief in several mountain ranges (Adirondack, Catskill, Taconic, Green, and White Mountains), moderate relief in the dissected Appalachian Plateau and New England Uplands, and low relief in lowlands formerly occupied by proglacial lakes or marine waters (fig. 10A).

In general, the terrane is characterized by thin (generally less than 15 m) or patchy till and exposed bedrock on the uplands and fine- to coarse-grained stratified sediments in the valleys and lowland areas (figs. 2, 3, and 4). The till is mostly silty to sandy in texture. Till thickness ranges from about 100 m in the lee of some hills and in valleys transverse to ice flow, to a thin veneer or complete absence over the tops of hills (fig. 8). Where stratified sediments are present on hillsides, it is typically not saturated and serves as a recharge area for stratified sediments in valleys, rather than as an aquifer. A wide range of sediment texture and thickness is indicated by the well logs shown in figure 5 of Soller (1993), but most of the area is underlain by a glacial geologic framework of low stratigraphic complexity.

Terrane 1B—Generally Pre-Late Wisconsinan Sediments in Southern Ohio, Indiana, and Illinois

Hydrogeologic terrane 1B consists primarily of glacial sediments beyond the Late Wisconsinan ice margin in Ohio, Indiana, and Illinois, and in a small area of Kentucky. Streams in terrane 1B drain upland areas to the Ohio and Mississippi Rivers (fig. 10B). Silty till blankets the uplands and covers about 60 percent of the terrane, whereas stratified sediments are confined mostly to stream valleys and covers most of the remaining area (figs. 2 and 3). Quaternary sediments thin to the south, and sedimentary bedrock is extensively exposed near the limit of glacial ice, which covered the area in Illinoian time. The till in terrane 1B is older and more weathered than till in terranes north of the limit of Wisconsinan glaciation and, therefore, potentially has different hydraulic characteristics. Large areas covered by colluvial sediment are near the southern limit of the terrane. Terrane 1B also includes substantial areas of mostly Late Wisconsinan stratified sediments—outwash and eolian (loess) sediments are present in large valleys, such as the Illinois River, Rock River, and Wabash River valleys, and lacustrine sediment is present in tributaries of the Ohio River.

Terrane 1C—Older, Partially Eroded Glacial Sediments in Central Missouri

Hydrogeologic terrane 1C consists of older (pre-Illinoian) sediments in northern Missouri and northeastern Kansas (fig. 10C). These sediments are highly weathered and eroded and are composed of mostly silty to clayey till that thins to the south (fig. 3). Sedimentary bedrock is extensively exposed near the limit of glacial ice. This terrane also includes areas of Late Wisconsinan and Holocene alluvial sediment in the Missouri River and tributaries. The pre-Illinoian sediments were deposited within the terrane during several periods of glaciation, and the original glacial landforms have been eroded or covered with eolian sediment (loess). Till covers about one-half of the terrane, whereas large areas near the Missouri and Mississippi Rivers are covered by colluvial sediment and residual soil (fig. 2). Most of the remaining area is covered by alluvial sediment in valleys draining to these major rivers.

Terrane 1D—Older, Partially Eroded Glacial Sediments Around the Driftless Area

Hydrogeologic terrane 1D includes the Driftless Area and surrounding glaciated areas in Minnesota, Iowa, Wisconsin, and Illinois (fig. 10D). The Driftless Area is so named because the area was not glaciated during the Pleistocene, although stratified sediments were deposited within the area by meltwater streams that drained the adjacent ice margins. Terrane 1D is underlain almost entirely by sedimentary bedrock that is weathered and highly dissected. Within the Driftless Area, these rocks are overlain by colluvial sediment (fig. 2). Glacial sediments in the margins surrounding the Driftless Area are mostly silty till, and stratified sediments are most common north and east of the Driftless Area (fig. 3). To the north and east, the boundary is defined as the limit of Late Wisconsinan ice, whereas to the west the boundary roughly coincides with the western edge of the Paleozoic Plateau; there, the till is pre-Late Wisconsinan in age, is extensively eroded, and is patchy with extensive areas of exposed bedrock.

Terrane 1E—Late Wisconsinan Sediments Near Lakes Superior and Michigan

Hydrogeologic terrane 1E consists of patchy, Late Wisconsinan sediments on Michigan's Northern Peninsula, on Wisconsin's Door Peninsula, in northeastern Minnesota (fig. 10D). About 60 percent of this terrane is covered by silty to sandy till and has extensive areas of peat and stratified glacial sediments (lacustrine and outwash sediments), especially in Michigan (figs. 3 and 4). Quaternary sediments of this terrane mostly overlie sedimentary, igneous, and metamorphic rocks.

Terrane 1F—Thin Late Wisconsinan Sediments in Montana and North Dakota

Hydrogeologic terrane 1F consists of mostly thin Late Wisconsinan and some older sediments and exposed sedimentary bedrock in eastern Montana and western North and South Dakota (fig. 10E). On the uplands, these sediments are mostly thin (less than 15 m) or patchy, silty till, and fine- to coarse-grained stratified sediments with some till in the Missouri River valley and its tributaries (figs. 3 and 8). About 65 percent of the terrane is covered by colluvial sediment (South Dakota) and residual soil (Montana and North Dakota; figs. 2 and 3). A wide range of sediment texture and thickness is indicated by the well logs shown in figure 5 of Soller (1993), but most of the area is underlain by a glacial geologic framework of relatively low stratigraphic complexity.

Terrane 1G—Residual Soils and Sediments From the Cordilleran Ice Sheet

Hydrogeologic terrane 1G extends from the Rocky Mountains in Montana, west to Puget Sound in Washington (fig. 10F). This broad area is characterized mainly by residual soil in mountainous areas and glacial sediments deposited by the Cordilleran ice sheet and alpine glaciers, including patchy till on the uplands and fine- to coarse-grained stratified sediments in the valleys (figs. 2 and 3). This terrane is underlain by various types of bedrock, ranging from Archean metamorphic rock in Montana to Tertiary volcanic and sedimentary rock in the Puget Sound lowlands (fig. 4). Quaternary sediments in the lowlands compose the Puget Sound aquifer system and are underlain by Tertiary sediments. The physiography of this terrane varies considerably and includes high relief in the Cascade and Rocky Mountain ranges, moderate relief in the central Washington Okanogan Highlands, and low relief near Puget Sound (fig. 10F).

Hydrogeologic Terranes of Moderate Complexity

The following terranes are of moderate complexity with a cover of 30 to 40 m of Quaternary sediments.

Terrane 2A—Predominantly Late Wisconsinan Sediments, Notably With Buried Valley Systems

Hydrogeologic terrane 2A consists of a nearly continuous cover of Quaternary sediments that overlies sedimentary bedrock and extends from Wisconsin, through Illinois, Indiana, and Ohio, and into Michigan (fig. 10B). Silty till predominates on the uplands and covers 70 percent of the terrane (fig. 3). Stratified sediments are mostly confined to stream valleys, except along the shores of Lakes Michigan, Erie, and Huron, where broad areas of proglacial lacustrine sediment cover 15 percent of the terrane (figs. 2 and 3). Clayey till occupies lowlands southwest of Lakes Michigan and Erie, which are remnants of advances of the Michigan and Huron-Erie ice lobes (fig. 3). A succession of end moraines in

Illinois, Indiana, and Ohio mark positions where these lobes stalled during the glacial retreat (fig. 2). Most of this terrane is underlain by carbonate bedrock (fig. 4); bedrock aquifers are hydraulically connected to Quaternary aquifers, especially in eastern Indiana and western Ohio, where together they are treated as a single aquifer system (Eberts and George, 2000).

Quaternary sediments at land surface are almost entirely of Late Wisconsinan age; Illinoian and older glacial sediments are preserved at depth (for example, within the Mahomet-Lafayette aquifer system of Ohio, Indiana, and Illinois) and over other bedrock topographic lows (fig. 10B). The variability of sediment texture, lithology and hydrogeologic characteristics is higher compared to the lower complexity terranes described in previous sections. The example well logs in Soller (1998), especially for Illinois and Indiana, give some indication of this variability at depth. The southern limit of this terrane is defined as the farthest extent of Late Wisconsinan glaciation. The eastern and northern boundaries are arbitrarily placed within transitional areas between adjacent terranes.

Terrane 2B—Late Wisconsinan Sediments From Lake Superior Lobe

Hydrogeologic terrane 2B consists of a nearly continuous cover of mostly Late Wisconsinan sediments deposited by the Lake Superior lobe over sedimentary, igneous, and metamorphic rocks in northern Wisconsin and eastern Minnesota (fig. 10D). Silty to sandy till covers 55 percent of the terrane (figs. 2 and 3). The remainder is covered by an extensive area of coarse-grained stratified sediments, primarily in the eastern part of the terrane and southwest of Lake Superior (fig. 3). The example well logs in Soller (1998) for Wisconsin convey the level of complexity of sediment deposits in this terrane. The southern limit of the terrane is defined as the farthest extent of Late Wisconsinan glaciation. Other boundaries are arbitrarily placed within transitional areas between adjacent terranes.

Terrane 2C—Late Wisconsinan Sediments in the Des Moines Lobe

Hydrogeologic terrane 2C consists of a continuous cover of Quaternary sediments that overlies sedimentary bedrock in Iowa and southern Minnesota (figs. 4 and 10C). Silty till predominates on the uplands and covers 80 percent of the terrane, whereas coarse-grained, stratified sediments are confined generally to stream valleys (figs. 2 and 3). Quaternary sediments at land surface are of Late Wisconsinan age deposited by ice of the Des Moines lobe that advanced to the east of the Prairie Coteau; at depth, older sediments are preserved (fig. 10C). The southern and eastern limit of this terrane is defined as the farthest extent of Late Wisconsinan glaciation. Other terrane boundaries are arbitrarily placed within transitional areas between adjacent terranes.

Terrane 2D—Older Sediments in Iowa and Kansas

Hydrogeologic terrane 2D consists of older (mostly pre-Illinoian) sediments that overlie sedimentary bedrock south

of the Late Wisconsinan ice margin in Kansas, Missouri, Iowa, and southeastern Minnesota (fig. 10C). Silty to clayey till predominates on the uplands and covers nearly 80 percent of the terrane, becoming mostly silty to the east (figs. 2 and 3). Eolian sediment (loess) blankets the uplands to a notable degree, exceeding 6 m in thickness in the western part of the terrane. Coarse-grained, stratified sediments (mostly alluvial sediment) are generally confined to stream valleys. Example well logs in Soller (1997; IA-1, IA-3, IA-4, and IA-5) give some indication of this variability at depth. The boundaries are arbitrarily placed within transitional areas between adjacent terranes, except where it abuts terrane 2C; there it is defined as the maximum extent of Late Wisconsinan glaciation.

Terrane 2E—Late Wisconsinan Sediments in the Dakotas

Hydrogeologic terrane 2E consists of a nearly continuous cover of Quaternary sediments that overlies sedimentary rocks in eastern North and South Dakota (fig. 10E). Silty till predominates on the uplands and covers 70 percent of the terrane (figs. 2 and 3). Broad areas of coarse- and fine-grained stratified sediments also are present on some uplands, which are dotted with prairie potholes, or kettle lakes. Fine-grained lacustrine sediment from proglacial lakes occupy lowlands along the Souris and James Rivers (figs. 2 and 10E). Quaternary sediments at land surface are mostly of Late Wisconsinan age, whereas older sediments are preserved beyond the Late Wisconsinan ice margin and at depth. Example well logs in Soller (1997; ND-1 and ND-2) give some indication of variability in areas with a thicker sediment cover. The boundaries are arbitrarily placed within transitional areas between adjacent terranes.

Hydrogeologic Terranes of Higher Complexity

The following terranes are of higher complexity with a thick (more than 60 m) cover of Quaternary sediments.

Terrane 3A—Interlobate Area in Southern Michigan Between Lake Michigan, Saginaw, and Lake Huron-Erie Lobes

Hydrogeologic terrane 3A consists of thick sequences of Quaternary sediments composed of multiple till sheets and intercalated stratified sediments (mostly sands and gravels) that overlie sedimentary bedrock Michigan's Southern Peninsula (figs. 2, 3, and 10B). This terrane is roughly delineated by the interlobate region between the ice sheets of the Michigan and Huron-Erie lobes. Sediment thickness commonly exceeds 100 m in the northern part of the terrane (fig. 8). Till is mostly sandy to silty in texture and covers 45 percent of the terrane (fig. 2). Stratified sediments are widespread at land surface and is mostly coarse-grained, except for fine-grained, lacustrine sediment in the lowlands southwest of Saginaw Bay (figs. 8 and 10B). The example well logs in Soller (1998) for Michigan convey the level of complexity of sediments in this terrane. The boundaries of this terrane mainly are based on the sediment thickness (fig. 8).

Terrane 3B—Interlobate Area in Minnesota Between Labrador and Keewatin Laurentide Centers

Hydrogeologic terrane 3B consists of thick sequences of Quaternary sediments composed of multiple till sheets and intercalated stratified sediments (mostly sands and gravels) over sedimentary, igneous, and metamorphic rock in Minnesota and the eastern Dakotas (figs. 2, 3, and 10D). Quaternary sediments were deposited by ice from the western and eastern centers of ice accumulation in the Laurentide ice sheet (Leverett and Sardeson, 1932; Mickelson and others, 1983). Ice flowed south from the western center in the Red River lobe, whereas ice flowed southwest from the eastern center in the Lake Superior lobe (lobes were centered in Canada north of the Red River and north of Lake Superior, respectively; fig. 10D). The interaction between these ice lobes formed a thick, highly complex stack of sediments that is poorly delineated in the subsurface. Sediment thickness commonly exceeds 100 m throughout the terrane (fig. 8). Till is silty sandy to clayey in texture and covers 45 percent of the terrane (figs. 2 and 3). Stratified sediments are mostly outwash sediment with some lacustrine sediment in the Red River valley, the former location of glacial Lake Agassiz (fig. 10D). Extensive deposits of peat in northern Minnesota cover 7 percent of this terrane.

Terrane 3C—Prairie Coteau

Hydrogeologic terrane 3C consists of thick sequences of Quaternary sediments beneath the Prairie Coteau region (eastern South Dakota, southwestern Minnesota, and northwestern Iowa), composed of multiple till sheets and intercalated stratified sediments (mostly sands and gravels) over sedimentary bedrock (fig. 10C). Quaternary sediments beneath the Prairie Coteau were deposited from interaction of ice in the interlobate region between the James and Des Moines lobes. Sediment thickness commonly exceeds 100 m, and silty till predominates at land surface and covers 80 percent of the terrane (figs. 2 and 3). Most of the coarse-grained sediments are outwash sediment deposited in the valleys of the Big and Little Sioux Rivers, but extensive ice-contact sediment mantles the uplands in the northern part of the terrane. The example well log in Soller (1997) for South Dakota conveys the level of complexity of sediments in this terrane (Soller, 1997). The boundaries of the terrane are based mostly on sediment thickness and topographic expression of the Prairie Coteau region (figs. 8 and 10C).

Hydrogeologic Terranes with Thick, Coarse-Grained, Stratified Quaternary Sediments

The following terranes contain a thick (70 to 90 m) cover of Quaternary sediments and have unique glacial settings.

Terrane 4A—Long Island and Cape Cod

Hydrogeologic terrane 4A includes glaciated areas on Cape Cod and Long Island (fig. 10A). Quaternary aquifers

beneath Long Island and Cape Cod are bounded by saltwater. On Long Island, the glaciated area extends from the north shore to the Ronkonkoma terminal moraine, which bisects the island west to east. Outwash plains that extend south of the moraine to the south shore are excluded in our definition of the glaciated United States. All of Cape Cod is included, however, because geologic units below the Quaternary sediments are not used as aquifers like they are on Long Island. Both areas are blanketed by thick morainal and intermorainal glacial sediments, and some thin postglacial alluvial, organic (peat), and eolian sediment are present in lowland areas. Morainal sediments mark the highest elevations on these islands. Maximum relief is about 93 m on Cape Cod and about 122 m on Long Island.

Quaternary sediments on Cape Cod are primarily outwash and ice-contact sands and gravels that directly overlies bedrock. Glacial deposition is the result of the interaction among the Buzzard's Bay, the Cape Cod Bay, and the South Channel ice lobes (Oldale and Barlow, 1986). Deposition from the Buzzard's Bay and the Cape Cod Bay lobes formed the high topography in western and northwestern Cape Cod, whereas deposition from the Cape Cod Bay and the South Channel lobes formed the low topography in the north-south "arm" of eastern Cape Cod. Outwash plains on Cape Cod cap a deltaic, downward fining sequence (Masterson and others, 1997; Walter and Whealon, 2005). The deltas were deposited into a proglacial lake that was dammed by a moraine near Martha's Vineyard and Nantucket to the south.

Quaternary sediments on Long Island overlie the dissected surface of unconsolidated Cretaceous-age sediments that contain two productive aquifers, the Magothy and the Lloyd aquifers (Smolensky and others, 1989). The Harbor Hill and the Ronkonkoma moraines form the north and south forks of Long Island, respectively, and coalesce into a single moraine across the western one-third of the island. The moraines are underlain by alternating till and outwash or ice-contact sediments. Intermorainal areas are underlain by outwash and interbedded lacustrine sediments (Krulikas and Kozalka, 1983).

Terrane 4B—Eastern Nebraska

Hydrogeologic terrane 4B consists of coarse-grained, stratified Quaternary sediments in eastern Nebraska (figs. 3 and 10C). Sediments were derived from the Laurentide ice sheet to the east and from the glacial and fluvial systems in the Rocky Mountains to the west. Terrane 4B also includes buried, pre-Illinoian till from the Laurentide ice sheet. The western boundary of the terrane is positioned just west of the till, whose position and geometry is arbitrary; hence the boundary is approximate and represented on the maps as an undulating line (fig. 2). Alluvial sediment covers 60 percent of the terrane, and silty clayey till covers most of the remainder (figs. 2 and 3).

Interpretive and Application Limitations

Any classification should be used with caution and understanding of the caveats. This is especially true for highly generalized, regional ones such as these hydrogeologic terranes. Here are the two principal caveats:

Variability within a terrane.—To achieve a manageable number of elements in this classification, hydrogeologic variations within a delineated terrane are acknowledged as likely. These variations are commonly indicated by well logs whose profiles do not match the generalized description for the terrane.

Similarity between terranes, especially near the boundaries.—Certain terrane boundaries are based on well-delineated geologic criteria (for example, the limit of Late Wisconsinan ice). Many other boundaries are less precisely positioned, on the basis of regional changes in overall thickness of Quaternary sediments or along regional trends of end moraines. In certain cases, the boundaries were arbitrarily drawn along State boundaries. The terrane boundaries therefore should be considered as “fuzzy” in nature, positioned in a very general sense, with considerable similarities shared by the geologic framework near the boundary on both sides.

Public-Supply Groundwater Use Datasets

Records of public-supply groundwater usage were collected for parts of 24 States within the glaciated conterminous United States (excluding Kentucky) for water systems that withdraw groundwater through wells and springs. The 71,267 public water systems that were identified included community systems, noncommunity systems with at least 15 service connections, and systems that regularly serve at least 25 individuals daily for at least 60 days each year. The status of water sources, whether active or inactive, was based on available State records. The compilation of groundwater-use information prepared for this study includes withdrawals from wells that derive water from surface-water infiltration, and groundwater delivered from combined systems that derive water from both groundwater and surface-water sources.

Water-use data, listed as a system-level table that lists information by system and as a source-level table that lists information by well, are published in Haj and others (2018). The water-use records include identifiers for the U.S. Environmental Protection Agency (EPA) and State agency databases, the ownership and type of public water system (PWS), the location and the population served by the system, withdrawal rates, well construction data, and the source aquifer of the water supply. The water-use records were sought for the reporting years 2009 to 2013 and averaged to compare with the 2010 data from the most recent USGS national water-use compilation (Maupin and others, 2014). The desired data for each record typically were not available from a single database. As a result, information on withdrawal rates, well construction, and aquifer source were compiled from and cross-referenced to those in State and Federal databases. A summary

of public-supply groundwater usage by State is presented in table 4 (in back of report), and the list of attributes included in the system and source tables is presented in table 5.

Most of the water-use records have location and population served data obtained from the EPA Safe Drinking Water Information System (SDWIS; U.S. Environmental Protection Agency, 2013). Additional records and information concerning SDWIS locations, for example well construction or source water databases, were obtained from State resources. Missing location data were approximated based on facility addresses or the central coordinates of the community served. Missing data on the population served were back-calculated from withdrawal rates or approximated by the median population served value for the public water system type within the State. In cases where population data were not available a default value of 25 persons was assumed, based on the minimum population required for a public water system. It is possible that some populations were double counted if a system sold water to another system, or for systems with groundwater and surface-water supplies that report combined values for the populations served.

Reporting of groundwater-use data varies among the States; for example, the withdrawal-rate reporting threshold ranged from 38 to 380 cubic meters per day, and records were reported by either the individual source or for the entire water system. Withdrawal data were obtained from the States' water-use registration, permitting, reporting, or allocation programs. Some withdrawal data were supplemented with information from the USGS Site-Specific Water-Use Data System (SWUDS; U.S. Geological Survey, 1997) and by direct requests to State agencies or through various online resources, such as water-quality and water diversion reports. Withdrawals from small water systems typically are not recorded and were estimated based on population served and a per capita water-use coefficient.

Per capita water-use values were obtained from the USGS Aggregate Water-Use Data System (AWUDS) database for 2010 (U.S. Geological Survey, 1998) and used either a county per capita value or a weighted average per capita for the State based on county populations. A public-supply per capita was commonly used to estimate withdrawals for mixed-use community water systems (for example, a city that delivers water to industrial, commercial, and residential customers). USGS public-supply data in AWUDS typically only included water-use data for community water systems that meet State reporting requirements and, in some cases, captured only the larger municipal water systems. Public-supply per capita water-use values ranged from 0.11 to 2.0 cubic meters per person per day (m^3ppd). Domestic per capita water-use values that ranged from 0.12 to 0.74 m^3ppd were estimated for residential community water systems that mainly serve households. Per capita values for transient, noncommunity systems (such as schools and offices) and nontransient, noncommunity systems (such as hotels and restaurants) were calculated from Vickers' industrial, commercial, and institutional benchmark data for similar public-supply uses (Vickers, 2001).

Table 5. Fields included in system-level and source-level water-use tables.

[EPA, U.S. Environmental Protection Agency; ID, identifier]

Field name	Table	Description	Values
AQ_CODE_TX	System and source	Type of aquifer source	Bedrock, bedrock aquifer type (consolidated rock, including fractured crystalline rock). Cretaceous, unconsolidated deposits of the Cretaceous Period ¹ . Mixed, water source or system open to multiple aquifer sources ² . Quaternary, unconsolidated materials of the Quaternary Period. Unknown, unknown aquifer type. NA, not available, used for water sources listed as a cross-connection to a neighboring water system.
CC_FLAG	System and source	Cross-connection data flag	Y, yes; groundwater is entirely purchased from a neighboring water system(s). N, no; no purchases are made, the system is solely supplied by its own groundwater sources. B, both; water supply is augmented by a purchase from neighboring water system(s).
CDEPTH_FT	Source	Casing depth	Depth in feet below land surface.
COEF_GPPD	System	Per capita water-use coefficient ³	Water use, in gallons per person per day.
COUNTY1	System and source	Name of county served by water system	Primary county of water service.
CTBG_GEOID	Source	Location of water source assigned to a Census block group	U.S. Census Bureau's TIGER/Lines shapefile for 2015 block groups. Field called "GEOID" represents the geographical area unit. Spatial data available at https://www.census.gov/cgi-bin/geo/shapefiles/index.php .
CTCS_GEOID	System	Location of water system assigned to a Census county subdivision	U.S. Census Bureau's TIGER/Lines shapefile for 2015 county subdivisions. Field called "GEOID" represents the geographical area unit. Spatial data available at https://www.census.gov/cgi-bin/geo/shapefiles/index.php .
FIPS1	System and source	State and county code	Primary county of water service defined by the five-digit Federal Information Processing Standard (FIPS) county code; available at https://www.census.gov/geo/reference/codes/cou.html .
OWNRTYPE	System	Owner type of the water system	F, Federal Government. L, local government. M, mixed public-private ownership. N, Native American government. P, privately owned. S, State government.
POP_FLAG	System	Population served data flag	Y, population served value likely contains persons served by surface water or may include double-counting of persons that purchase groundwater from another system. C, population served value of a mixed water systems (has both surface- and groundwater sources) was adjusted to account for persons only served by groundwater. N, population served by groundwater.
POP_X-CTY	System	Multi-county water service data flag	Y, population served by the public-water system extends across state or county boundaries. N, population served by the public-water system is within one county.
POPSRV_PERS	System	Population served value	Population, by groundwater, in persons. See field called "POP_FLAG" for data qualifiers.
PWS_ID	System and source	Public-water system identifier ⁴	EPA's Safe Drinking Water Information System (SDWIS) database.
PWS_NAME	System and source	Public-water system name ⁵	EPA's Safe Drinking Water Information System (SDWIS) database.

Table 5. Fields included in system-level and source-level water-use tables.—Continued

[EPA, U.S. Environmental Protection Agency; ID, identifier]

Field name	Table	Description	Values
PWS_TYPE	System and source	Public-water system type	CWS: community. NTNCWS: nontransient, noncommunity ⁶ . TNCWS: transient, noncommunity ⁷ .
REC_NO	Source	Source record number	Sequential record number of the source-level table starting at 1.
SELLER1_PWSID	System	PWS_ID of a neighboring water system from which water is purchased	First listed PWS_ID selling water to the local water system.
SELLER2_PWSID			Second listed PWS_ID selling water to the local water system.
SELLER3_PWSID			Third listed PWS_ID selling water to the local water system.
SELLER4_PWSID			Fourth listed PWS_ID selling water to the local water system.
SELLER5_PWSID			Fifth listed PWS_ID selling water to the local water system.
SELLER6_PWSID			Sixth listed PWS_ID selling water to the local water system.
SRC_STATUS	Source	Groundwater source production status in 2010	A, active. E, active but reserved for backup or emergency use. I, inactive. L, legacy (water system no longer uses their wells but purchases groundwater from another system; however, the purchased amount was not reported in the seller's reported withdrawal data). R, assumed to be active. T, to be abandoned. X, abandoned.
SRC_TYPE	Source	Groundwater source type	WL, well. SP, spring. CC-GW, groundwater purchased through a cross-connection to neighboring water system(s).
SRC_WD-GW_MGY	Source	Withdrawal from a groundwater source	Well or spring, in million gallons per year.
STATE1	System and source	State	Primary state of water service represented by the 2-letter U.S. Postal Service abbreviation.
SYS_WD-GW_MGY	System	Total groundwater withdrawal ⁸ by the water system	In million gallons per year.
SYS_WTR_TYPE	System	Water source ⁹ served by the water system	GW, groundwater. BOTH, groundwater and surface water.
WDEPTH_FT	Source	Well depth	In feet below land surface.
WU_METH	System and source	Method used to obtain the groundwater-use value	R, Reported data. E, Estimated value. B, Combination of both approaches (for example, system had reported withdrawals for some but not all of its groundwater sources or system had reported total withdrawal but no withdrawal data by its sources).

¹For example, Magothy and Llyod aquifers of Long Island, New York.²For example, Quaternary and bedrock, Quaternary and Cretaceous.³Used if system withdrawals were estimated.⁴Unassigned values given project-specific sequential ID beginning sys00001.⁵Preference was given to State-designated system names when merging records from multiple data sources.⁶For example, schools and offices.⁷For example, hotels and restaurants.⁸Indicates that water is supplied and accounted for by a neighboring water system.⁹Systems that serve surface water exclusively were not included.

The transient noncommunity water use per capita value was 0.06 m³ppd and the nontransient, noncommunity water use per capita value was 0.19 m³ppd.

Assigning the source aquifer, either Quaternary sediments or bedrock, for each water system was difficult because few States provide an aquifer code in their water-use reporting databases and well construction data were often not available or readily cross-referenced. State websites and map services were searched to obtain information on aquifer resources, including maps of depth to bedrock, Quaternary sediment thickness, and surficial geology. In cases where source aquifer or well construction data were available, the records were matched and classified. If well construction data were available, then assignments were based on well depth in comparison to the available maps or spatial proximity to nearby adjacent well records with more complete data.

If well construction data were not available, two other methods were used to assign the source aquifer. For counties where a predominant aquifer source could be determined from either other public-supply well records that contained aquifer codes or additional data from the USGS National Water Information System (NWIS; U.S. Geological Survey, 2015), the aquifer source was assigned to the County's predominant aquifer source. If no predominant aquifer source was apparent, then the aquifer source was assigned using a map of Quaternary sediment thickness (Soller and Garrity, 2018). Water systems were assigned to either a bedrock aquifer or a Quaternary aquifer if the well was located where the sediment thickness was thin or thick (less than 15 m or greater than 60 m, respectively). The aquifer source was not assigned for the 7,276 remaining water systems where the sediment thickness was between 15 and 60 m.

The public water system records were checked to improve quality and completeness of inventories and associated data. Several checks were implemented, including searching for outliers, missing, or irregular data entries; removing duplicate records that resulted from the merger of State and Federal records; and reviewing the accuracy of data codes, units, and water-use estimation methods that were based on various types of public water systems. Per capita use values were calculated for each system and evaluated to determine whether the reported withdrawal rates were reasonable. Common errors that were corrected include population counts for facilities that deliver water to other facilities, populations that were counted at the source and destination facilities, and withdrawal rates for mixed-use supplies that provide water for manufacturing.

The completed inventory represents the best estimates of public-supply groundwater withdrawals by source aquifer, on the basis of the current state of scientific knowledge and data available. Annual public-supply, groundwater withdrawals in 2010, aggregated by State, are compared with estimates from Maupin and others (2014; fig. 11). The total withdrawals estimated for the glaciated United States are similar (5,527 million cubic meters per year in this study and 5,082 million cubic meters per year in Maupin and others, [2014]), but the

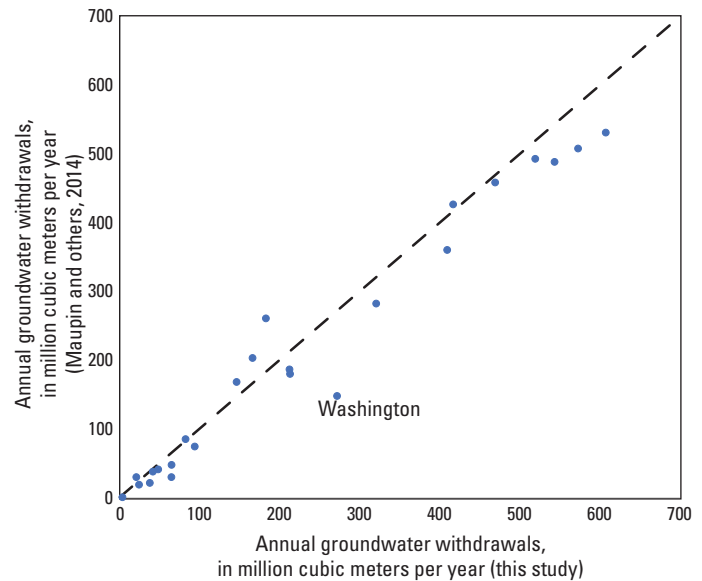


Figure 11. Comparison of public-supply groundwater withdrawals in the glaciated conterminous United States estimated by this study and by Maupin and others (2014).

withdrawals estimated for some States (for example, Washington) are different. In some cases, public-water supplies in the SWUDS database used in this study were mislabeled as surface water, rather than groundwater, leading to under estimation. In other cases, per capita values used to estimate groundwater withdrawals by Maupin and others (2014) were too large, particularly in areas where water supplies serve non-public users, resulting in overestimation of actual withdrawals for public supply. Additional information, beyond the scope of this study, is required to account for all these differences.

Lithologic Database Derivatives

A lithologic database for the glaciated conterminous United States was compiled from State well records, and the well records were standardized so that the lithologic information used a consistent terminology (Bayless and others, 2017). The part of the database used for this study contains 1,565,349 records in 24 States in the glaciated conterminous United States (excluding Kentucky), of which 740,727 are for wells that are for the purpose of withdrawing water. Most of the records for water wells in the database are for domestic wells. The data density varies: about 85 percent of the well records are in the Midwest, 13 percent are in the Northeast (terrane 1A and 4A), and 2 percent are in the Northwest (terrane 1G; fig. 12). The data density reflects areas where groundwater usage is highest (terrane 1B, 2A and 3B), and States that possess the most complete well records (for example, Vermont). Three States, Connecticut, Nebraska, and Michigan, do not record the usage of the well, so no information is available concerning the distribution of water wells.

Figure 12. Density of lithologic logs aggregated on a 5-kilometer grid in the glaciated conterminous United States. Map is available at <https://doi.org/10.3133/ds1090>.

The lithologic database contained the top and bottom depth for intervals with the lithologic descriptions (lithologic logs), as well as various other items describing the wells on a State-by-State basis. A composite database was created by combining all the States and aggregating the individual intervals for each well into a single record. The well locations were intersected with the spatial datasets of the hydrogeologic terranes and from the GESS geodatabase. Attributes were added to the records for each well in the lithologic database describing the hydrogeologic terrane, the complexity of the hydrogeologic terrane, the surficial map unit, the texture of the surficial unit, whether the unit was stratified and coarse, and the bedrock geology classification (table 6). Characteristics of the Quaternary sediments encountered by the wells were calculated from the lithologic data, as described below. The metrics that were compiled from the lithologic database are listed in table 6. Median values of each metric were aggregated using a 1-km geospatial grid cell to deemphasize clusters in the data. The gridded lithologic database can be accessed at Haj and others (2018).

The Quaternary sediment thickness was computed if the depth to bedrock was noted in the lithologic log. Not all wells penetrated the entire thickness of Quaternary sediments, especially in areas where the sediments are thickest, such as in terranes of high complexity (codes 3 and 4). In the case where the log did not show bedrock contact, the thickness was estimated from the maps of the Quaternary sediment thickness.

For most of the area, the depth of the Quaternary sediments from Soller and Garrity (2018) was used. For the Puget Sound area, the bedrock surface from Jones (1999) was used. In a small area near Colville, Washington, the depth of the Quaternary sediments came from a groundwater-flow model (Ely and Kahle, 2004). In areas of eastern Washington, Idaho, and Western Montana, no previous estimates of the Quaternary sediment thickness were available on a regional basis.

Several metrics that characterize the Quaternary sediment and aquifer-material intervals (at least 3 m of coarse-grained material) penetrated by the wells were computed from the lithologic logs. For the purpose of these computations, the Quaternary sediments were classified into fine-grained (clay and silt) and coarse-grained (sand and gravel) categories. Aquifer material was considered to be 3 m or more of contiguous coarse-grained material within a lithologic log with no more than 0.5 m of intervening fine-grained material. The number of occurrences of aquifer-material intervals in each log was counted. The aquifer thickness, interval depth, thickness of the confining layer (if present), and the amount of fine-grained material within the aquifer-material interval were computed. In the case where multiple intervals were present, the values for the thickest (main) and deepest (bottom) intervals were recorded. In cases where only one interval of aquifer material was present, the main and bottom intervals are the same. Additional metrics were computed as to whether the aquifer-material interval was confined by at least 7.5, 15, or 30 m of fine-grained material. An important caveat is that some aquifer-material intervals shown by lithologic logs could be partially saturated, so the computed aquifer thickness would be greater than the saturated thickness of the aquifer.

Table 6. Characteristics of sediment and aquifer-material intervals obtained from lithologic logs.

[km, kilometer; m, meter; <, less than; >, greater than]

Variable	Definition
Log attribute	
ID	Well identifier.
State	State location.
Grid ID	Sequential number in 1-km grid.
Terrane	Hydrogeologic terrane.
WellDepth	Depth of lithologic log below land surface.
BedrockDepth	Depth bedrock below land surface.
BedrockDepthSource	Source of bedrock-depth data; from log, or estimated from Jones (1999), Ely and Kahle (2004), or Soller and Garrity (2018).
PercentLogPenetration	Percent penetration of log through Quaternary sediment.
NumberAquifers	Number aquifer-material intervals.
WaterTableAquiferThick	Thickness of aquifer-material interval overlain by <7.5 m of fine-grained material.
ConfinedAquifer	Aquifer-material interval overlain by >7.5 m of fine-grained material.
GESS_MU	Glacial Environment and Surficial Sediments (GESS) geodatabase map unit attribute (table 1).
Texture4	4-bin texture class (from table 3, with silty-clay and sandy-silt included as silty).
Texture6	6-bin texture class (table 3).
SiteUse	Monitoring or withdrawal well, or unknown.
WellSource	Waterwell source: Quaternary sediment or bedrock.
CrseStratSed	Log located in areas mapped as coarse stratified sediment (from GESS_MU and Texture6, table 2).
Class_1A	Topographic setting of log in terrane 1A.
Class_1G	Topographic setting of log in terrane 1G.
Stratified_1A	Log located in stratified drift aquifers mapped by Kontis and others (2004).
FirstBedrock	Bedrock lithology at bedrock surface noted in lithologic log.
Percentage of coarse material in Quaternary sediment	
PercentCoarse	Penetrated by log.
PercentCoarse7_5	Upper 7.5 m.
PercentCoarse15	Upper 15 m.
PercentCoarse30	Upper 30 m.
Thickest aquifer-material interval	
MainAquiferDepth	Depth.
MainAquiferThick	Thickness.
MainAquiferCL	Percentage of coarse material in sediment overlying aquifer-material interval.
Deepest aquifer-material interval	
BottomAquiferDepth	Depth.
BottomAquiferThick	Thickness.
BottomAquiferCL	Percentage of coarse material in sediment overlying aquifer-material interval.

Summary

The U.S. Geological Survey (USGS) has completed a study to assess the occurrence and characteristics of confined and unconfined glacial aquifers in the conterminous United States, their distribution and extent, and their potential intrinsic susceptibility and vulnerability. As part of that study, multiple hydrogeologic and geospatial datasets were organized into the hydrogeologic framework for the glacial aquifer system to three-dimensionally characterize the Quaternary sediments of the glaciated conterminous United States. These data were intended to aid in the identification and explanation of regional patterns in aquifer occurrence, productivity, and water quality in the glacial aquifer system. This report describes the components of the hydrogeologic framework: the Glacial Environments and Surficial Sediments (GESS) geodatabase, which includes lithologic, geomorphic, and stratigraphic characterization of surficial and glacial sediments; hydrogeologic terranes; public-supply and domestic well databases containing groundwater use information; and a geospatial framework for visualizing and interpreting available subsurface lithologic information derived from State-managed well records and geologic logs.

The GESS geodatabase—a geospatial framework that maps, categorizes, and characterizes the physical properties of the glacial sediments—was created from the Quaternary Atlas of the United States map series and the Map Database for Surficial Materials in the Conterminous United States geodatabases. The GESS geodatabase includes a map unit attribute (GESS_MU) with alluvial sediment, bedrock, colluvial sediment, eolian sediment, fill, ice-contact sediment, lacustrine sediment, marine sediment, organic sediment, outwash sediment, residual soil, solifluction sediment, till and water values; a geomorphic modifier attribute (GESS_Modifier) with “e” (end moraine), “g” (ground moraine), “s” (stagnation moraine), “d” (discontinuous or attenuated), and “p” (solifluction) values; attributes for stratified sediments and coarse-grained, stratified sediments (StratSed and CrseStratSed) to differentiate stratified, coarse-grained, stratified, and unstratified sediments; and a textural classification attribute (Texture6) with values of mostly sandy, sandy-silty, mostly silty, silty-clayey, mostly clayey, and mostly organic. Also included is a simplified bedrock geology dataset, an amalgamation of several Integrated Geologic Map Databases for the United States, for identification of potential areas of glacial aquifer and bedrock aquifer interaction. When interpreting or applying the GESS geodatabase attributes and values in a hydrogeologic context, several considerations must be made, such as the scale of the GESS geodatabase and the scale of the aquifer of interest, discontinuities in mapped features and lithological information at state and quadrangle map boundaries, and potential spatial discrepancies with spatial elements in the GESS geodatabase and other available geospatial datasets.

Hydrogeologic terranes were defined using four criteria: overall thickness of Quaternary sediments, the predominant modes of glacial deposition, the predominant texture of the

surficial sediments, and the geologic age of the sediments. The first of those criteria was used to infer, delineate, and qualitatively rank hydrogeologic complexity that may exist in each terrane: lower complexity, moderate complexity, or higher complexity. Terranes of similar complexity were then evaluated based upon the remaining criteria: mode of deposition, texture, and geologic age; letter designations were appended to the numeric codes for complexity (for example, 1A and 3C) to denote differences. According to this classification methodology, the Quaternary sediments within the glaciated area of the conterminous United States were classified into 17 hydrogeologic terranes.

The compilation of groundwater-use information prepared for this study includes withdrawals from wells that derive water from surface-water infiltration, and the groundwater part delivered from combined systems that derive water from groundwater and surface-water sources. Records of public-supply groundwater usage were collected for parts of 24 States within the glaciated conterminous United States (excluding Kentucky) for water systems that withdraw groundwater through wells and springs. Two tables were prepared for the water-use data: a system-level table that lists information by system and a source-level table that lists information by well. The water-use records include identifiers for the U.S. Environmental Protection Agency and State agency databases, the ownership and type of public water system, the location and the population served by the system, withdrawal rates, well construction data, and the source aquifer of the water supply. Withdrawal data were obtained from the States’ water-use registration, permitting, reporting, or allocation programs. Some withdrawal data were supplemented with information from the USGS Site-Specific Water-Use Data System (SWUDS) and by direct requests to State agencies or through various online resources, such as water-quality and water diversion reports. Per capita water-use values were obtained from the USGS Aggregate Water-Use Data System (AWUDS) database for 2010. Source aquifer, either Quaternary sediments or bedrock, were assigned for each public-water system based upon State-provided aquifer codes in their water-use reporting databases and well construction data if available, based on well depth in comparison to the available maps or spatial proximity to nearby adjacent well records with more complete data, or other methods. The public-water system records were checked to improve quality and completeness of inventories and associated data. The completed inventory represents the best estimates of public-supply groundwater withdrawals by source aquifer on the basis of the current state of scientific knowledge and data available.

A lithologic database for the glaciated conterminous United States was compiled from State well records, and lithologic logs consisting of 1,565,349 records in 24 States in the glaciated conterminous United States (excluding Kentucky), of which 740,727 are for wells that are for the purpose of withdrawing water. The well locations were intersected with the spatial datasets of the hydrogeologic terranes and from the GESS geodatabase. Attributes were added to the records for

each well in the lithologic database describing the hydrogeologic terrane, the complexity of the hydrogeologic terrane, the surficial map unit, the texture of the surficial unit, the bedrock geology classification, and whether the unit was stratified and coarse. Characteristics of the Quaternary sediments penetrated by the wells were calculated from the lithologic data. The Quaternary sediment thickness was computed if the depth to bedrock was noted in the lithologic log. Several metrics that characterize the Quaternary sediments and potential aquifer materials penetrated by the wells were computed from the lithologic logs. Quaternary sediment was classified into fine-grained (clay and silt) and coarse-grained (sand and gravel) categories. Aquifer material was considered to be 3 meters or more of contiguous coarse-grained material within a lithologic log with no more than 0.5 meter of intervening fine-grained material. The number of occurrences of aquifer-material intervals in each log was counted. The thickness, depth, thickness of the confining layer (if present), and the amount of fine-grained material within the aquifer-material interval were computed. Additional metrics were computed as to whether the aquifer-material interval was confined by at least 7.5, 15, or 30 meters of fine-grained material. Median values of each metric were aggregated using a 1-kilometer geospatial grid cell to deemphasize clusters in the data.

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Table 4

Table 4. Groundwater usage for public-supply water systems, by State, in the glaciated conterminous United States.

[A public water-supply (PWS) system is a system for the provision to the public of piped water for human consumption that has at least 15 service connections, or regularly serves an average of at least 25 individuals daily at least 60 days out of the year. Usage has been divided into community and noncommunity water systems. Summarized water-use data are from 2009 to 2013. —, no value determined]

Public water system type or aquifer source	Total systems	Community water systems ¹	Noncommunity water systems ¹
Glaciated conterminous United States (all or parts of 24 States)			
Water systems	71,566	14,097	57,469
Population served, in thousands	42,198	34,839	7,360
Groundwater usage, in million cubic meters per year	5,527	5,271	255
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	2,697	2,611	86.2
Bedrock ⁴	1,666	1,551	116
Mixed ⁵	1,033	1,015	18.7
Unknown ⁶	130.1	95.4	34.7
Connecticut (100 percent of counties)			
Water systems	2,375	481	1,894
Population served, in thousands	1,218	1,055	163
Groundwater usage, in million cubic meters per year	213	204	8.58
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	12.7	12.6	0.0886
Bedrock ⁴	114	106	8.49
Mixed ⁵	85.6	85.6	—
Unknown ⁶	—	—	—
Idaho (2.5 percent of counties)			
Water systems	99	35	64
Population served, in thousands	14.7	10.8	3.96
Groundwater usage, in million cubic meters per year	3.14	3.02	0.116
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	3.14	3.02	0.112
Bedrock ⁴	—	—	—
Mixed ⁵	0.00415	—	0.00415
Unknown ⁶	—	—	—
Illinois (93.8 percent of counties)			
Water systems	3,407	1,227	2,180
Population served, in thousands	4,426	4,080	346
Groundwater usage, in million cubic meters per year	519	507	12.0
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	220	218	2.44
Bedrock ⁴	159	157	2.64
Mixed ⁵	133	133	—
Unknown ⁶	6.96	0.0644	6.90
Indiana (84.3 percent of counties)			
Water systems	3,442	628	2,814
Population served, in thousands	3,402	2,897	506
Groundwater usage, in million cubic meters per year	469	450	19.3
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	342	335	6.73
Bedrock ⁴	25.1	23.3	1.84
Mixed ⁵	87.2	87.2	—
Unknown ⁶	15.1	4.42	10.7

Table 4. Groundwater usage for public-supply water systems, by State, in the glaciated conterminous United States.
—Continued

[A public water-supply (PWS) system is a system for the provision to the public of piped water for human consumption that has at least 15 service connections, or regularly serves an average of at least 25 individuals daily at least 60 days out of the year. Usage has been divided into community and noncommunity water systems. Summarized water-use data are from 2009 to 2013. —, no value determined]

Public water system type or aquifer source	Total systems	Community water systems ¹	Noncommunity water systems ¹
Iowa (100 percent of counties)			
Water systems	1,743	981	762
Population served, in thousands	2,274	2,151	123
Groundwater usage, in million cubic meters per year	416	412	4.95
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	232	231	1.02
Bedrock ⁴	162	159	3.58
Mixed ⁵	21.8	21.7	0.0167
Unknown ⁶	0.336	0.00400	0.332
Kansas (8.3 percent of counties)			
Water systems	131	129	2
Population served, in thousands	442	442	0.150
Groundwater usage, in million cubic meters per year	64.3	64.3	0.009
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	64.3	64.3	0.00915
Bedrock ⁴	—	—	—
Mixed ⁵	—	—	—
Unknown ⁶	—	—	—
Maine (100 percent of counties)			
Water systems	1,420	301	1,119
Population served, in thousands	406	207	199
Groundwater usage, in million cubic meters per year	41.3	34.6	6.72
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	29.2	29.0	0.237
Bedrock ⁴	10.1	4.41	5.71
Mixed ⁵	1.15	1.15	—
Unknown ⁶	0.773	0.00625	0.767
Massachusetts (100 percent of counties)			
Water systems	1,448	331	1,117
Population served, in thousands	1,802	1,587	214
Groundwater usage, in million cubic meters per year	182	176	6.49
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	169	167	2.491
Bedrock ⁴	7.52	3.84	3.69
Mixed ⁵	5.03	5.03	—
Unknown ⁶	0.770	0.453	0.317
Michigan (100 percent of counties)			
Water systems	15,076	1,081	13,995
Population served, in thousands	2,998	1,619	1,380
Groundwater usage, in million cubic meters per year	320	276	44.0
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	191	169	22.5
Bedrock ⁴	108	91.4	16.6
Mixed ⁵	17.5	15.4	2.11
Unknown ⁶	3.40	0.608	2.79

Table 4. Groundwater usage for public-supply water systems, by State, in the glaciated conterminous United States.
—Continued

[A public water-supply (PWS) system is a system for the provision to the public of piped water for human consumption that has at least 15 service connections, or regularly serves an average of at least 25 individuals daily at least 60 days out of the year. Usage has been divided into community and noncommunity water systems. Summarized water-use data are from 2009 to 2013. —, no value determined]

Public water system type or aquifer source	Total systems	Community water systems ¹	Noncommunity water systems ¹
Minnesota (100 percent of counties)			
Water systems	6,781	904	5,877
Population served, in thousands	3,763	3,163	601
Groundwater usage, in million cubic meters per year	543	527	16.4
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	126	119	6.73
Bedrock ⁴	317	314	3.18
Mixed ⁵	92.8	92.7	0.106
Unknown ⁶	7.55	1.15	6.41
Missouri (36.5 percent of counties)			
Water systems	296	257	39
Population served, in thousands	864	852	12.3
Groundwater usage, in million cubic meters per year	146	144	1.80
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	7.53	7.53	—
Bedrock ⁴	124	123	1.77
Mixed ⁵	12.3	12.3	—
Unknown ⁶	1.67	1.64	0.0276
Montana (34.6 percent of counties)			
Water systems	544	198	346
Population served, in thousands	145	96.4	48.6
Groundwater usage, in million cubic meters per year	20.5	18.9	1.62
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	14.8	14.1	0.620
Bedrock ⁴	5.77	4.77	0.999
Mixed ⁵	—	—	—
Unknown ⁶	—	—	—
Water systems	583	313	270
Nebraska (21.6 percent of counties)			
Population served, in thousands	705	663	41.7
Groundwater usage, in million cubic meters per year	166	164	2.26
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	49.6	48.8	0.803
Bedrock ⁴	4.59	4.17	0.421
Mixed ⁵	112	111	1.03
Unknown ⁶	—	—	—
New Hampshire (100 percent of counties)			
Water systems	2,217	645	1,572
Population served, in thousands	774	478	297
Groundwater usage, in million cubic meters per year	64.5	53.3	11.3
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	4.62	4.10	0.512
Bedrock ⁴	58.5	47.7	10.8
Mixed ⁵	1.41	1.41	—
Unknown ⁶	—	—	—

Table 4. Groundwater usage for public-supply water systems, by State, in the glaciated conterminous United States.
—Continued

[A public water-supply (PWS) system is a system for the provision to the public of piped water for human consumption that has at least 15 service connections, or regularly serves an average of at least 25 individuals daily at least 60 days out of the year. Usage has been divided into community and noncommunity water systems. Summarized water-use data are from 2009 to 2013. —, no value determined]

Public water system type or aquifer source	Total systems	Community water systems ¹	Noncommunity water systems ¹
New Jersey (33.2 percent of counties)			
Water systems	1,214	191	1,023
Population served, in thousands	1,489	1,231	259
Groundwater usage, in million cubic meters per year	213	200.4	12.3
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	20.9	18.8	2.11
Bedrock ⁴	107.8	97.6	10.2
Mixed ⁵	68.0	68.0	—
Unknown ⁶	16.0	16.0	—
New York (98 percent of counties)			
Water systems	7,494	1,639	5,855
Population served, in thousands	4,474	3,659	815
Groundwater usage, in million cubic meters per year	607	580	27.2
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	147	128	19.3
Bedrock ⁴	⁷ 100	⁷ 100	0.01
Mixed ⁵	299	291	7.90
Unknown ⁶	61.3	61.3	—
North Dakota (85.1 percent of counties)			
Water systems	345	211	134
Population served, in thousands	299	285	13.6
Groundwater usage, in million cubic meters per year	47.8	47.3	0.486
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	44.3	44.1	0.202
Bedrock ⁴	2.78	2.60	0.180
Mixed ⁵	0.0555	0.0555	—
Unknown ⁶	0.734	0.629	0.104
Ohio (71.8 percent of counties)			
Water systems	3,911	812	3,099
Population served, in thousands	5,119	4,588	531
Groundwater usage, in million cubic meters per year	573	552	20.4
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	495	491	4.04
Bedrock ⁴	48.7	42.6	6.08
Mixed ⁵	23.7	16.9	6.85
Unknown ⁶	5.31	1.90	3.42
Pennsylvania (31.7 percent of counties)			
Water systems	3,604	665	2,939
Population served, in thousands	970	484	486
Groundwater usage, in million cubic meters per year	82.2	63.6	18.6
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	19.6	19.5	0.0387
Bedrock ⁴	49.4	33.4	16.0
Mixed ⁵	3.89	3.89	—
Unknown ⁶	9.4	6.77	2.60

Table 4. Groundwater usage for public-supply water systems, by State, in the glaciated conterminous United States.
—Continued

[A public water-supply (PWS) system is a system for the provision to the public of piped water for human consumption that has at least 15 service connections, or regularly serves an average of at least 25 individuals daily at least 60 days out of the year. Usage has been divided into community and noncommunity water systems. Summarized water-use data are from 2009 to 2013. —, no value determined]

Public water system type or aquifer source	Total systems	Community water systems ¹	Noncommunity water systems ¹
Rhode Island (100 percent of counties)			
Water systems	441	64	377
Population served, in thousands	336	256	79.5
Groundwater usage, in million cubic meters per year	37.4	34.4	2.96
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	30.9	30.6	0.330
Bedrock ⁴	6.29	3.80	2.49
Mixed ⁵	0.194	0.0520	0.142
Unknown ⁶	0.0371	0.0341	0.00298
South Dakota (51.1 percent of counties)			
Water systems	165	152	13
Population served, in thousands	423	419	3.52
Groundwater usage, in million cubic meters per year	93.6	93.5	0.083
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	83.5	83.4	0.0656
Bedrock ⁴	9.14	9.12	0.0178
Mixed ⁵	0.942	0.942	—
Unknown ⁶	0.0151	0.0151	—
Vermont (100 percent of counties)			
Water systems	1,097	308	789
Population served, in thousands	295	174	121
Groundwater usage, in million cubic meters per year	24.0	19.7	4.34
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	9.72	7.87	1.85
Bedrock ⁴	14.3	11.8	2.49
Mixed ⁵	—	—	—
Unknown ⁶	—	—	—
Washington (48.7 percent of counties)			
Water systems	2,230	1,434	796
Population served, in thousands	2,312	2,136	176
Groundwater usage, in million cubic meters per year	271	266	5.79
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	268	262	5.79
Bedrock ⁴	0.213	0.213	—
Mixed ⁵	3.33	3.33	—
Unknown ⁶	0.281	0.281	—

Table 4. Groundwater usage for public-supply water systems, by State, in the glaciated conterminous United States.
—Continued

[A public water-supply (PWS) system is a system for the provision to the public of piped water for human consumption that has at least 15 service connections, or regularly serves an average of at least 25 individuals daily at least 60 days out of the year. Usage has been divided into community and noncommunity water systems. Summarized water-use data are from 2009 to 2013. —, no value determined]

Public water system type or aquifer source	Total systems	Community water systems ¹	Noncommunity water systems ¹
Wisconsin (100 percent of counties)			
Water systems	11,503	1,110	10,393
Population served, in thousands	3,248	2,308	940
Groundwater usage, in million cubic meters per year	409	381	27.8
Usage by aquifer source, in million cubic meters per year:			
Quaternary sediment ³	112	104	8.15
Bedrock ⁴	231	212	18.8
Mixed ⁵	65.2	64.7	0.505
Unknown ⁶	0.492	0.153	0.339

¹Community water system is a PWS that serves at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents. Examples are cities, rural water districts, correctional facilities, and mobile home parks.

²Noncommunity water system is a PWS that is not a community water system. There are two types: Nontransient, noncommunity water systems regularly serve at least 25 of the same persons over 6 months per year. Examples include day care facilities, factories, schools, and office buildings. Transient, noncommunity water systems provide water in a place where people do not remain for long periods of time. Potable use is for more than 25 persons at least 60 days of the year. Examples include hotels, restaurants, retail stores, and churches.

³Quaternary sediments include materials of glacial, postglacial, and nonglacial origin.

⁴Bedrock is composed of consolidated material such as sedimentary, carbonate, metamorphic, plutonic, or volcanic rock. Cretaceous sediments for Long Island, New York, were assigned to this aquifer source.

⁵Mixed is an aquifer that includes both Quaternary sediments and bedrock aquifers.

⁶Indicates that the aquifer could not be determined.

⁷Total includes 71 million cubic meters per year from bedrock aquifers in upstate New York and 29 million cubic meters per year from Cretaceous sediments on Long Island.

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