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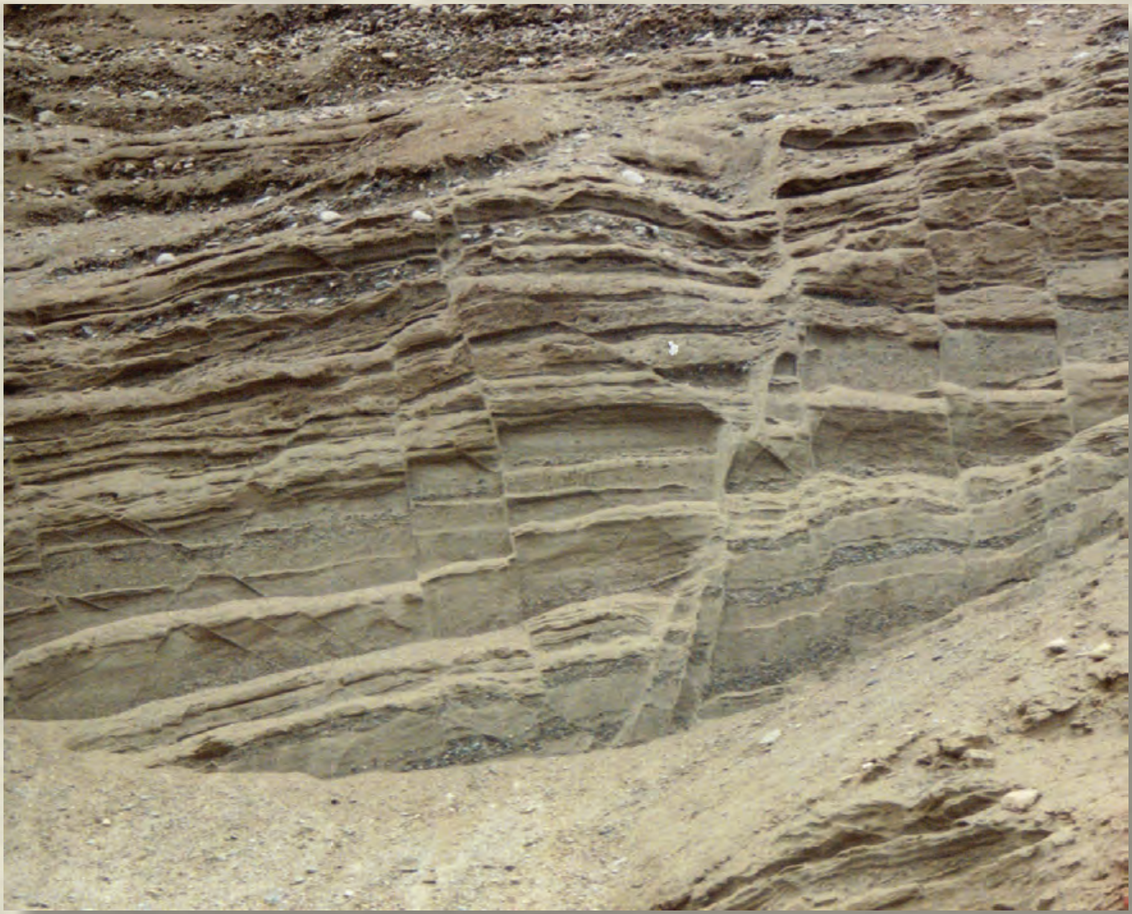
Generalized Hydrogeologic Framework and Groundwater Budget for a Groundwater Availability Study for the Glacial Aquifer System of the United States



Scientific Investigations Report 2017–5015

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

Cover: Glacial outwash near Ely, Minnesota. Photograph by Christopher Hoard, U.S. Geological Survey.

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By H.W. Reeves, E.R. Bayless, R.W. Dudley, D.T. Feinstein, M.N. Fienen, C.J. Hoard, G.A. Hodgkins, S.L. Qi, J.L. Roth, and J.J. Trost

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Conversion Factors

[U.S. customary units to International System of Units]

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	0.01427	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year	25.4	millimeter per year (mm/yr)

[International System of Units to U.S. customary units]

Multiply	By	To obtain
	Length	
kilometer (km)	0.6214	mile (mi)
	Volume	
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Flow rate	
meter per year (m/yr)	3.281	foot per year ft/yr)

Datum

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

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

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

Abbreviations

BFI	Base-flow index
GAGES II	Geospatial Attributes of Gages for Evaluating Streamflow, version II
GRACE	Gravity Recovery and Climate Experiment
HYSEP	Hydrograph separation program
NAWQA	National Water-Quality Assessment
RASA	Regional Aquifer-System Analysis
SMCL	Secondary Maximum Contaminant Level
SWB	Soil Water Balance
USGS	U.S. Geological Survey

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Abstract

The glacial aquifer system groundwater availability study seeks to quantify (1) the status of groundwater resources in the glacial aquifer system, (2) how these resources have changed over time, and (3) likely system response to future changes in anthropogenic and environmental conditions. The glacial aquifer system extends from Maine to Alaska, although the focus of this report is the part of the system in the conterminous United States east of the Rocky Mountains. The glacial sand and gravel principal aquifer is the largest source of public and self-supplied industrial supply for any principal aquifer and also is an important source for irrigation supply. Despite its importance for water supply, water levels in the glacial aquifer system are generally stable varying with climate and only locally from pumping. The hydrogeologic framework developed for this study includes the information from water-well records and classification of material types from surficial geologic maps into likely aquifers dominated by sand and gravel deposits. Generalized groundwater budgets across the study area highlight the variation in recharge and discharge primarily driven by climate.

Introduction

The Glacial Aquifer System Groundwater Availability Study assesses groundwater availability for the expansive and diverse glacial aquifer system of the United States. The glacial aquifer system is present in parts of 26 States and is subject to a range of climatic conditions: humid to semiarid, maritime to continental to arctic. Groundwater availability in the system may be constrained by climatic conditions, poor water quality from natural or anthropogenic constituents, hydrogeology, competing uses, or the discharge needed to maintain or restore environmental streamflows. The glacial aquifer system is a major source of water for public, self-supplied domestic and industrial, and irrigation water use (Maupin and Barber, 2005). The study seeks to quantify (1) the status of groundwater resources in the glacial aquifer system, (2) how these resources have changed over time, and (3) likely system response to future changes in anthropogenic and environmental conditions.

Background

The U.S. Geological Survey (USGS) Groundwater Resources Program (now incorporated into the Water Availability and Use Science Program) began an assessment of groundwater availability in the principal aquifers of the United States in 2004. Several studies have been completed: Northern Atlantic Coastal Plain Aquifer System, Columbia Plateau Regional Aquifer System, High Plains Aquifers, Mississippi Embayment Regional Aquifer Study, Great Basin Carbonate and Alluvial Aquifer System, Central Valley Aquifer, North and South Carolina Atlantic Coastal Plain Aquifer System, Denver Basin Aquifer, and Middle Rio Grande Basin Study; several are underway in addition to the Glacial Aquifer System: Pacific Northwest Volcanic Aquifer System, Pennsylvanian and Mississippian Aquifer System of the Appalachian Plateaus, Ozark Plateaus Aquifer System, Hawaii Volcanic-Rock Aquifers, Williston and Powder River Basins, and Floridan Aquifer System (U.S. Geological Survey, 2017). These regional studies aim to provide the required information for a national assessment of groundwater resources. The glacial aquifer system often begins at land surface, which makes it vulnerable to contamination from surface activities and important in providing base flow to streams. The vast extent, heterogeneity of aquifer material, and range of climatic conditions for the glacial aquifer system impose challenges to this regional groundwater availability study.

The glacial geology of North America has been studied for more than 150 years: “*The literature of American glacial geology is already very extensive, and every year is adding to its bulk * * *. It is no exaggeration to say, that, the whole surface of North America, from the shores of the Arctic Ocean to the latitude of New York, and from the Pacific to the Atlantic, has been scarped, scraped, furrowed, and scoured by the action of ice*” (Giekie, 1874). Despite changes in the interpretation of the mechanisms of glaciation that led to modern conditions, the work of scientists interpreting the glaciated landscape, including Hitchcock (1841), Agassiz (1876), Chamberlain (1894, 1895), Leverett and Taylor (1915), and numerous others, is the foundation of scientific interpretation of glacial geology. Importantly, the practice of interpreting glacial geology based on the modern-day landforms resulting from glacial action emanates from these early studies and shapes modern approaches based on morphostratigraphy (Frye and Willman, 1962) or morphosequences (Koteff and Pessl, 1981; Stone and Stone, 2005). From the perspective of groundwater resources, depositional features have attendant aquifer properties and the hydrogeologic framework for the glacial aquifer system relies on interpretation of glacial geology informed by previous work in hydrogeology across parts of the glacial aquifer system (Eyles, 1983; Eyles and others, 1985; Anderson, 1989).

Climatic conditions, including average precipitation, temperature, and wind speed, directly affect groundwater availability. The recharge to groundwater in semiarid or arid regions may be so low that withdrawals from the system lead to groundwater mining and depletion of the resource; however, the effects of climatic conditions in parts of the glacial aquifer system may be more subtle. Seasonal, annual, or decadal variations in climate can lead to changes in the recharge to the groundwater system and the demands on the system for public, domestic, irrigation, and industrial supply. The combined effect of lower recharge and higher demand may be transient, but it can have undesired consequences such as land subsidence, temporary streamflow depletion, water levels dropping below the level of existing pumps or wells, and migration of poor-quality water into the aquifer. Understanding climatic variations and the effects on the groundwater system is important because these undesired conditions may occur in an area that appears to have sufficient surface-water and groundwater resources to meet demands if only average conditions are considered.

Study Area

The glacial aquifer system in the United States extends from Maine to Alaska (fig. 1). The system is made of material deposited by Laurentide and Cordilleran ice sheets (fig. 2) that extended into North America in series of advances and retreats of continental glaciers between 2.5 million and 12,000 years ago (Dorr and Eshman, 1970; Booth and others, 2003; Marshall and others, 2003; Mickelson and Colgan, 2003). In some areas, later glaciation removed old material and only material from the last advance is found; but, in other areas, glacial deposits from sequential advances and retreats are present. The dynamics of deglaciation and the resulting landforms and glacial geology are subjects of much research that can help provide a foundation for the glacial aquifer system study. The glacial landforms and land systems have characteristic material that affects groundwater yield, aquifer hydraulic properties, and, ultimately, groundwater availability at both local and regional scales (Eyles, 1983; Eyles and others, 1985; Anderson, 1989).

The deposits that form the glacial aquifer system are dominated by material deposited by continental glaciation; however, material of more recent deposition is present in the study area. Much of the alluvial deposits in the study area are comprised of material originally deposited by glaciers that has subsequently been transported and reworked. Classifying these alluvial deposits separately from glacial deposits at the scale of the study area would unnecessarily complicate the regional analysis. All unconsolidated material north of the extent of glaciation, including recent glacial deposits in areas such as Alaska, will be considered as part of the glacial aquifer system even if the material has been deposited more recently by other mechanisms.

Large continental glaciers, including those that deposited the material in the glacial aquifer system study area, affect groundwater systems in ways other than deposition of material (Callegary and others, 2013). These continental glaciers can profoundly change hydraulic pressures and force freshwater into the underlying unconsolidated and consolidated materials, and this introduction of water can lead to geochemical alteration (Person and others, 2007). High hydraulic pressures and loading by glaciers can deform geologic units, fracture bedrock, and change porosity and permeability. These other features of glacial interaction with groundwater are not discussed as part of the framework.

The glacial sand and gravel principal aquifer as defined by Miller (1999) and studied as part of the northeast Regional Aquifer-System Analysis (RASA) (Haeni, 1995; Randall, 2001; Kontis and others, 2004) was defined to include sand and gravel deposits from the Laurentide ice sheet and not the Cordilleran deposits in the western continental United States and Alaska; therefore, the glacial sand and gravel principal aquifer is contained within the glacial aquifer system. This groundwater availability study follows the study area established for the National Water-Quality Assessment (NAWQA) Project (Warner and Arnold, 2006) and includes the entire glacial aquifer system. This definition of the study area is broader than the glacial sand and gravel principal aquifer because (1) the regional contributions of the material from the Cordilleran ice sheet to estimates of groundwater availability are included, and (2) low conductivity material associated with glacial deposits may be important in contributing to groundwater availability. The study area is quite broad because, for areas glaciated by either the Laurentide or Cordilleran ice sheet, water from domestic wells for potable supply and local wells for irrigation or industrial use may be produced from glacial deposits with low hydraulic conductivity or local isolated sand or gravel units that are typically not mapped as sand and gravel aquifers. Deposits with lower hydraulic conductivity also contribute important storage to the system and can be important to water availability and water-quality characteristics anywhere in the system.

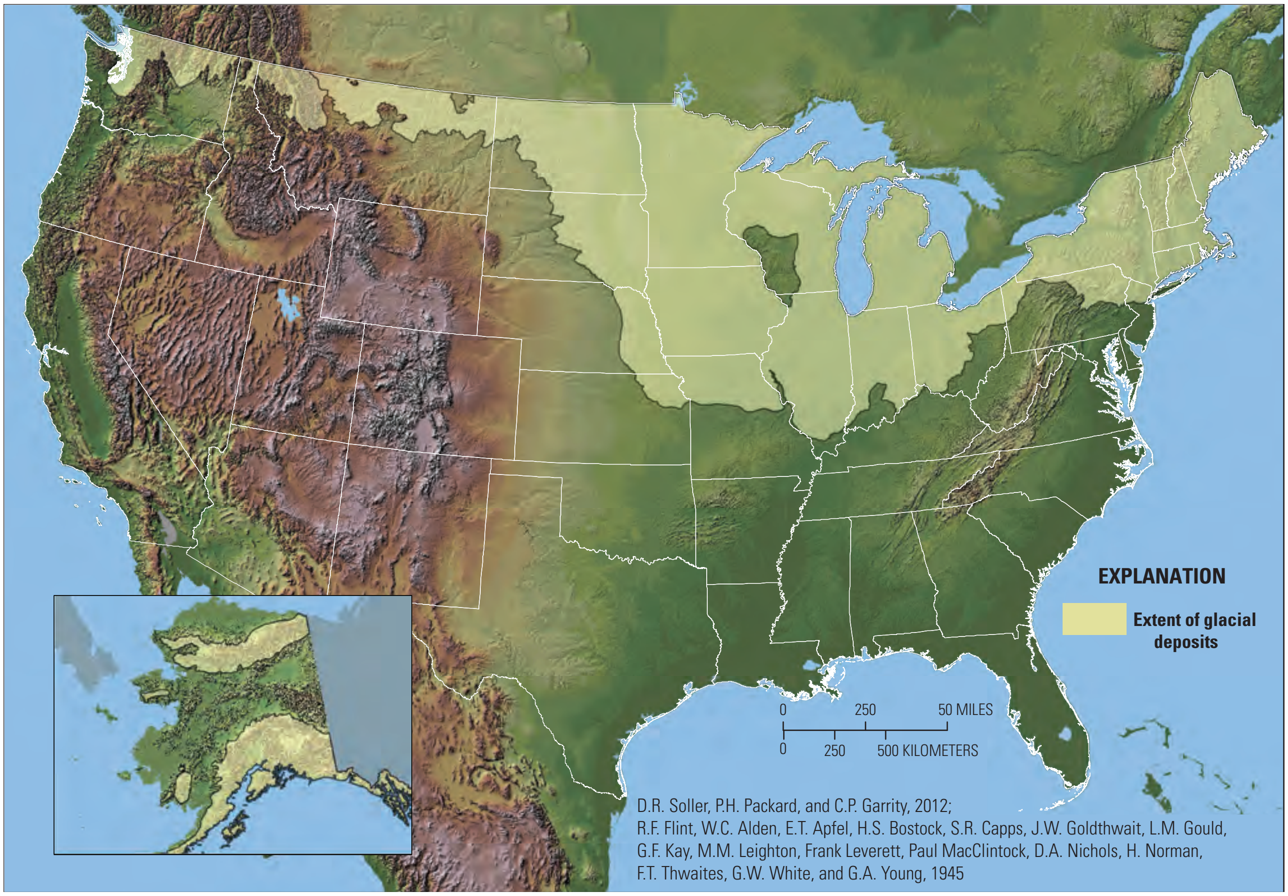


Figure 1. Study area for glacial aquifer study includes areas glaciated by the Laurentide and Cordilleran ice sheets.

The study area was divided into four regions for the NAWQA glacial principal aquifer study (fig. 3) (Warner and Ayotte, 2014). The NAWQA regions were developed to classify the glacial aquifer system based on two factors: (1) intrinsic susceptibility to contamination, and (2) vulnerability of the aquifer to contamination. Intrinsic susceptibility depends only on the physical characteristics of the aquifer and the ease at which contaminants may move through the aquifer system. Vulnerability, however, considers both intrinsic susceptibility and the potential for contamination based on sources, the characteristics of potential contaminants, and the geochemical conditions of the aquifer (Warner and Arnold, 2006). The characteristics of these regions are summarized in table 1. These regions will be retained in this report to facilitate future incorporation of the water-quality characteristics of the glacial aquifer system noted by Warner and Ayotte (2014) into water budget analysis presented in this report. The groundwater availability analysis additionally will benefit from the previous NAWQA regional assessment (Warner and Ayotte, 2014), and results from the availability analysis may be used to support continued regional work (Burow and Belitz, 2014).

Hydrogeology Overview

The hydrogeology of the glacial aquifer system varies as reflected by regional spatial landforms and has notable heterogeneity at local scales. The materials deposited by glaciers range in size from clay particles to boulders. Drift refers to all material transported and ultimately deposited by glaciers through various mechanisms (Foster, 1983). Depositional features fall broadly into two classes: (1) till features, which comprise material deposited by glacial ice as unsorted mixtures of sizes; and (2) outwash features, which are deposited by glacial meltwater, tend to be more sorted, and may be coarse grained (Dorr and Eshman, 1970). In this report, till will refer to all unsorted to poorly sorted deposits associated with glaciers from various mechanisms. Till features tend to have relatively low hydraulic conductivity and may locally serve as confining units, whereas outwash features often have higher hydraulic conductivity and may be local aquifers. Variations in local terminology, however, can lead to contradictions of these generalizations. In some parts of the study area, units described as coarse tills may be marginal aquifers. In all parts of the study area, deposits often show abrupt changes in lithology at local scales, and aquifers may be difficult to identify and correlate in space.

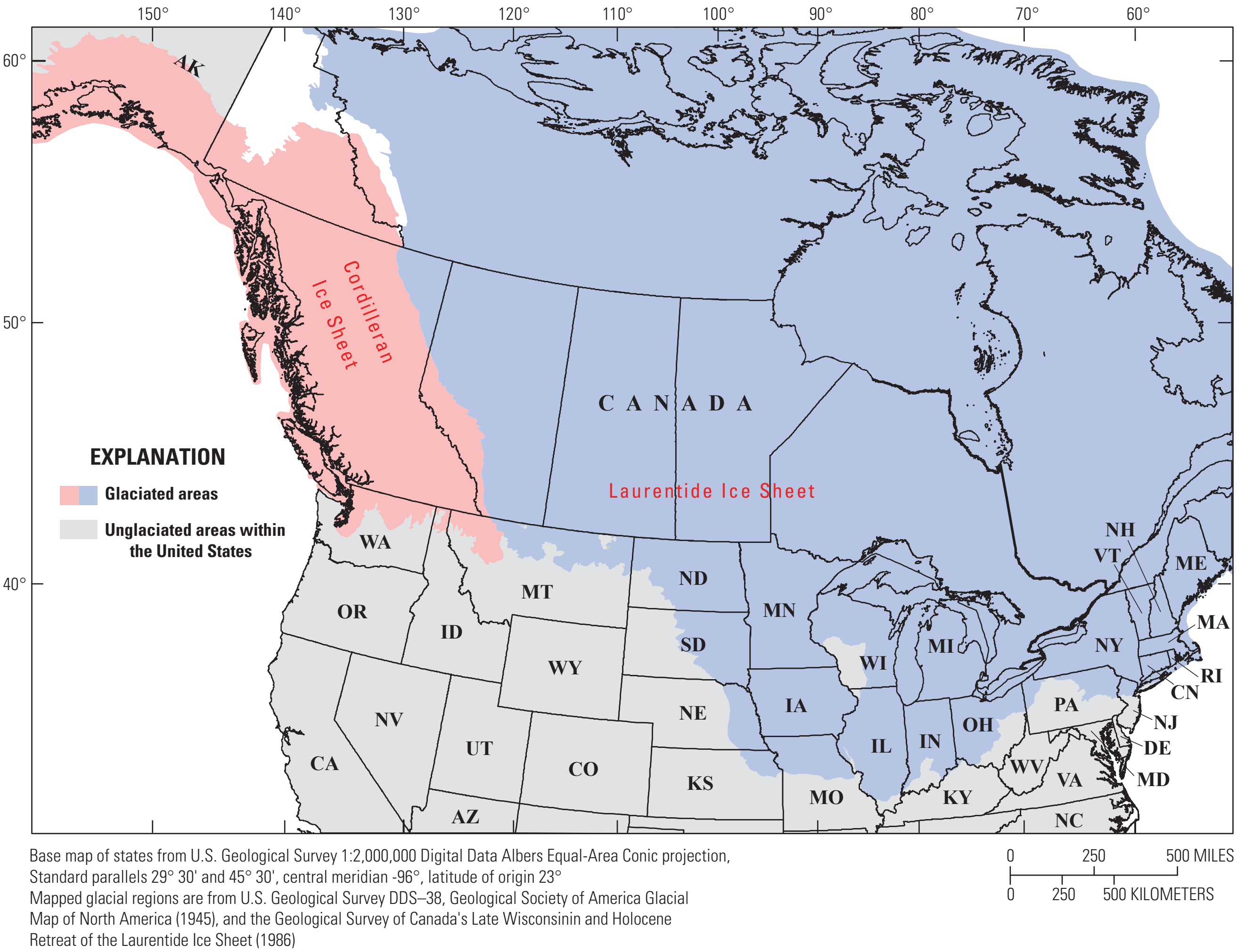


Figure 2. Location of continental ice sheets relevant to the glacial aquifer system regional groundwater availability study (modified from Bayless and others, 2017).

A glaciated area in North Dakota provides one example of this complexity as exhibited in a prairie wetland complex. This wetland complex is located on the Coteau du Missouri, a glacial moraine formed by highly heterogeneous glacial tills that can contain individual fluvial deposits of sand and gravel within a clay matrix of low permeability. This setting helps control the location and behavior of the wetland complex that often has seasonal flow reversals in the groundwater system between aquifers and local wetlands (Winter, 2003). Other glacial settings across the glacial aquifer system exhibit different depositional features and different hydrogeologic controls on groundwater flow. Challenges to this study include synthesizing numerous studies of the geology and hydrogeology conducted at various spatial scales across the glacial aquifer system to assess regional groundwater availability.

Climate

Climate varies substantially across the glacial aquifer system. For example, the average annual precipitation from 1981 to 2010 was less than 10 inches (in.) in parts of Montana and North Dakota and over 70 in. in the Northwest Pacific and parts of Alaska (National Oceanic and Atmospheric Administration, 2017a, b). This variation is coupled with hydrogeologic conditions to provide a major control on the groundwater availability of the system.

Purpose and Scope

In this report, several hydrogeologic frameworks for the glacial aquifer system will be assessed for use in understanding groundwater availability of the aquifer. The framework is designed to focus the study on aspects of the system that control groundwater availability. The developed framework also will be used to relate groundwater availability analysis from a water budget and potential constraint framework to previous synthesis of groundwater quality for the glacial aquifer system. In addition to the hydrogeologic framework, estimated regional and subregional groundwater budgets are presented and discussed. The framework and

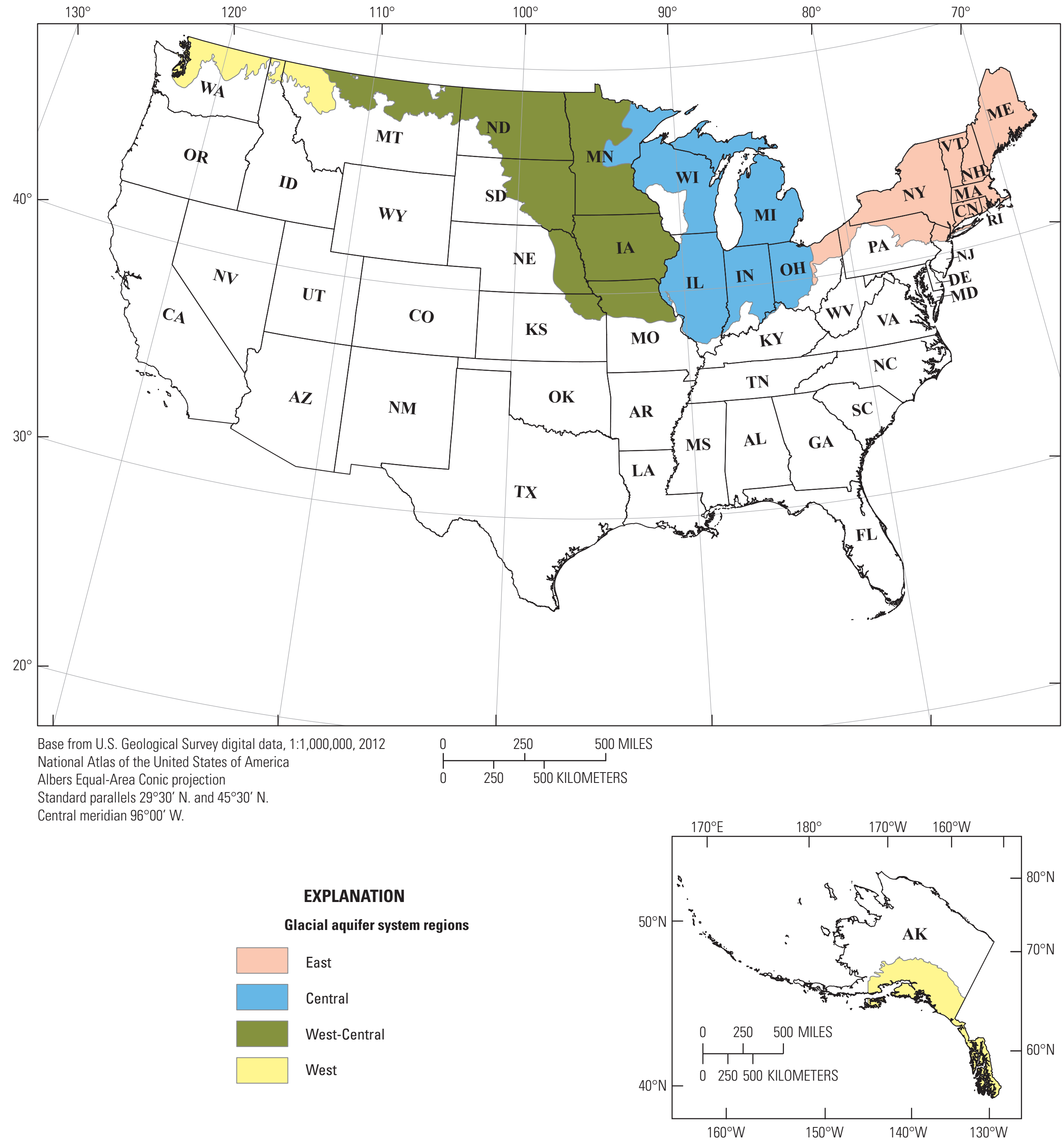


Figure 3. The four regions defined for the glacial aquifer system for the National Water-Quality Assessment (NAWQA) Project principal aquifer analysis (modified from Warner and Ayotte, 2014).

Table 1. Characterization of National Water-Quality Assessment Project regions used in the principal aquifer study (modified from Warner and Ayotte, 2014).

Characterization of glacial regions	East	Central	West-Central	West
Topography	Mountainous	Flat	Flat	Mountainous
Climate	Humid	Humid	Arid/humid	Arid/humid
Thickness	Moderately thin	Thick	Thick	Moderately thick
Characterization of sediment	Mixed—more coarse than fine	Mixed—more fine than coarse	Mixed – more fine than coarse	Mixed—more coarse than fine
Common bedrock	Crystalline	Carbonate	Shale and Carbonate	Crystalline
Major glacial aquifer use	Drinking water	Drinking water	Drinking water and irrigation	Drinking water and irrigation
Characteristic land use	Urban and forested	Agriculture	Agriculture	Forested and urban
Other principal aquifers underlying the glacial aquifer system	New York-New England carbonate-rock aquifers New England crystalline rock aquifer Early Mesozoic basin aquifer	Cambrian-Ordovician aquifer Silurian-Devonian aquifer Mississippian aquifer Pennsylvanian aquifer	Cambrian-Ordovician aquifer Silurian-Ordovician aquifer Mississippian aquifer High Plains aquifer Lower Tertiary sandstone Upper Cretaceous sandstone	none

groundwater budgets provide the foundation for numerical groundwater-flow models that can be developed as part of the study to quantify the response of parts of the glacial aquifer system to changes in groundwater withdrawals and climate. Groundwater-flow models are essential to groundwater availability studies because the effect of development on the system is estimated using these models, and groundwater availability may ultimately be determined through such an assessment of these effects. The scope of the report is the glacial aquifer system of the United States (fig. 1), although the major focus is on the part of the system in the conterminous United States east of the Rocky Mountains.

Groundwater Availability Issues for Glacial Aquifer System

The glacial aquifer system is unique among principal aquifers because of several factors including its large size, the range of climatic conditions across the system, and the diversity of hydrogeologic conditions within the system. The groundwater availability study must consider parts of the system that may be over 1,000 feet (ft) thick or less than a few feet thick, the hydraulic conductivity may range over several orders of magnitude, and the arrangement of the materials can vary from nearly uniform layers of gravel, sand, silt, or clay to poorly sorted mixtures of these materials. These factors lead to several issues confronting the groundwater availability study of the glacial aquifer system.

Heterogeneity of Glacial Deposits

Glacial deposits are quintessentially heterogeneous, and site-specific layers or lenses ranging from less than a foot to several feet thick and extending from tens to hundreds of feet may have profound consequences on local groundwater availability, especially in determining water-quality conditions that may either limit or provide potable water (Brusseau, 1994). Groundwater availability on a regional scale is less influenced by local heterogeneity because the general spatial patterns and temporal trends can be identified at the regional scale. Heterogeneity is acknowledged as crucial in the local interpretation of these patterns and trends; notably, local conditions may vary from the regional setting because of local depositional processes and the interaction between hydrogeology, climate, and local stresses such as pumping wells or land-use change.

Importance of Material with Low Hydraulic Conductivity

Previous regional studies on groundwater availability for parts of the glacial aquifer system include Vaccaro and others (1998), Randall (2001), and Kontis and others (2004), and the regional study in the northeastern United States (Randall, 2001; Kontis and others, 2004) focused on stratified sand and gravel aquifers. The USGS NAWQA Project synthesis for the glacial principal aquifer considered all unconsolidated material north of the extent of glaciation including clays and silts in addition to sands and gravels (Warner and Arnold, 2006). This report adopts the latter approach in order to include both productive sand and gravel deposits and less productive glacial deposits, all parts of the glacial aquifer system, to provide a context for groundwater availability analysis across the study area.

Groundwater Quality Limitations

Water-quality characteristics identified by the USGS NAWQA Project for the glacial aquifer system include (1) contaminants from geologic sources, in particular arsenic and manganese, are a potential concern for human health; (2) in agricultural areas, concentrations of nitrate and pesticides were usually low in groundwater associated with fine-grained glacial deposits but could be high in groundwater associated with coarse-grained glacial deposits; (3) in urban areas, chloride concentrations in groundwater tend to be increasing; and (4) 75 percent of samples from drinking-water wells in the glacial aquifer system had concentrations exceeding a U.S. Environmental Protection Agency secondary maximum contaminant level (SMCL) (Warner and Ayotte, 2014). The SMCLs are nonregulatory guidelines developed to advise decision makers and the public about issues such as unpleasant taste or odor; staining of skin or teeth; and staining of laundry, dishes, or plumbing fixtures. Iron was the most common constituent that exceeded the SMCL in the samples. Other constituents associated with exceedances in SMCL include manganese, chloride, sodium, sulfate, and aluminum. Water with exceedances in SMCL often also has high dissolved solids and hardness (Warner and Ayotte, 2014). Current NAWQA studies in the glacial aquifer system are aimed at monitoring to analyze trends and patterns and the development of tools to inform decision makers about potential water-quality issues and effects of management actions, particularly for groundwater accessed by public-supply wells (Rowe and others, 2013).

Groundwater/Surface-Water Interaction

Aquifers in glacial deposits are expected to be the shallowest aquifers across the study area; therefore, the interaction between groundwater and surface water is an important aspect of the glacial aquifer system. Groundwater provides base flow to streams across the study area (Winter and others, 1998; Healy and others, 2007; Reilly and others, 2008), and the relative amount of base flow to total streamflow for streams in the study area varies according to the hydrogeology of the glacial deposits and climatic factors. The base-flow index (BFI), ratio of base flow to total streamflow, across the conterminous United States is estimated to range from almost 6 percent to over 90 percent (fig. 4; Wolock, 2003a).

The importance of base flow in many parts of the study area has motivated a great deal of interest in potential streamflow depletion by pumping wells (Barlow and Leake, 2012), and several States in the study area, including Massachusetts, Michigan, Rhode Island, and Washington, have adopted regulations or management goals to maintain environmental flows in streams that consider the potential for streamflow depletion by wells (Kendy and others, 2012; State of Washington Department of Ecology, 2015).

Importance of Land Drainage Systems

Many parts of the study area, often where base flow index is shown to be low in figure 4, have been artificially drained by the installation of agricultural drainage tiles. This drainage lowers the average water table, and even though the lowering may be relatively small, on the order of 1–10 ft, the cumulative effect on the volume of groundwater stored in the glacial aquifer system can be quite large (Konikow, 2013). Drained glacial systems also have been recognized as important in the transport of nutrients and other constituents to streams (Dubrovsky and others, 2010; Minnesota Pollution Control Agency, 2013). As previously noted, in agricultural parts of the study area that are dominated by fine-grained material, groundwater may be low in nitrate and pesticides, but streams may have elevated concentrations because of transport of these constituents in tile systems. In parts of the system dominated by coarse-grained deposits, the aquifer system is more likely to have elevated nitrate or pesticide concentrations, and groundwater can transport these constituents to streams. Drainage tiles continue to be installed because of the agricultural benefits offered by controlling soil moisture, and the installation has been extended to areas where drains typically have not been used (Associated Press, 2013). Attention has been directed to the water-quality effects of agricultural land and the potential for streamflow depletion by pumping wells. To address concerns for both of these topics, control of runoff from tile drains coupled with appropriate irrigation has been proposed to increase food production, maintain environmental flows, and decrease runoff of nutrients linked to water-quality degradation in the Midwestern United States (Baker and others, 2012).

Importance of Spatial Scale

Understanding spatial scale and the relation between spatial scale, potential groundwater availability constraints, data requirements, and appropriate analytical approaches is very important for regional groundwater availability studies in order to match the scale of the analysis to the questions that can be addressed. Because of the large size of the study area, conditions and stresses in one part of the study area do not affect the entire study area. Questions related to the spatial scale of heterogeneities within glacial deposits or the effects of pumping from an aquifer on nearby surface-water features are appropriately addressed at the local scale. The study of site-specific groundwater availability conditions across the entire study area is infeasible; therefore, regional summaries will be sought in the analysis, and methods to estimate local responses within regional systems will be tested. The data and analysis used for the hydrogeologic frameworks and the groundwater availability questions addressed will be consistent with the scale of the analysis.

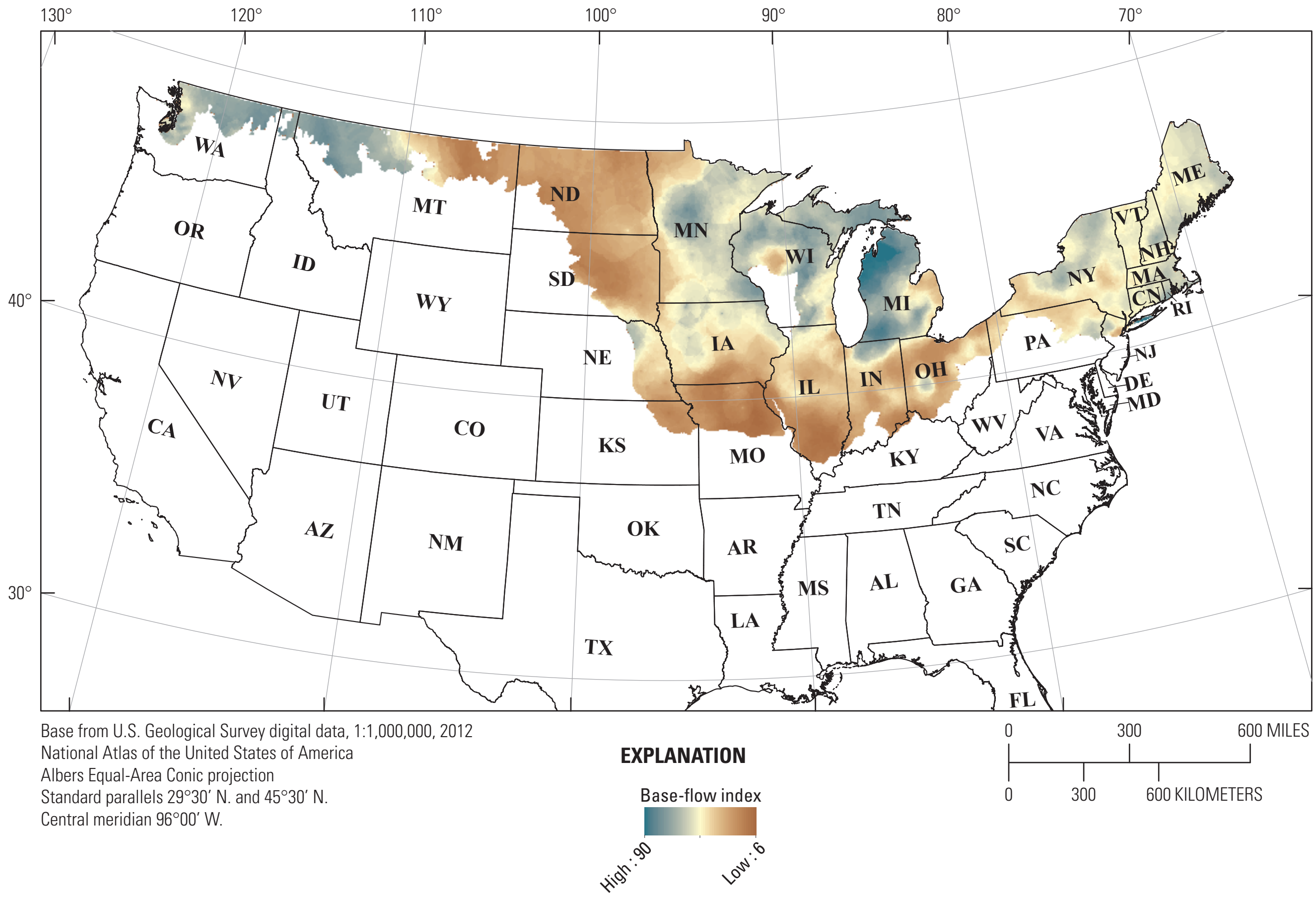


Figure 4. Base-flow index grid clipped to glacial extent (from Wolock, 2003a).

Approach

Groundwater availability depends on several factors: hydrogeology; climate; existing water use; and imposed social, economic, or legal constraints on groundwater extraction. The hydrogeology of a system determines how groundwater moves through the system, governs how quickly the system will respond to changes in external conditions such as changes in climate or pumping, and controls the volume of groundwater in storage. Climate determines the amount of water that might be available for recharge to the system. Climate also affects seasonal and long-term variations in groundwater levels. The response of the groundwater system to change, current water use, and constraints such as instream flow requirements determines the amount of groundwater that is economically available for use without an unacceptable effect on existing users or ecosystems.

Groundwater availability studies typically propose a hydrogeologic framework of the study area to define the system and focus efforts on the parts of the system that control groundwater availability (Masterson and others, 2013). The range of climatic and geologic conditions across the glacial aquifer system motivates development of a broad hydrogeologic framework that captures important factors that may control groundwater availability. A framework includes hydrogeology and components of the groundwater budget related to climate and water use.

Hydrogeologic Frameworks

Hydrologic frameworks for the glacial aquifer system are developed to describe the important features of the system that provide or limit groundwater across the study area. The frameworks are used to identify the features of the system used to quantify groundwater availability. Two main approaches to the framework are considered. The first approach is to adopt the four regions used by the USGS NAWQA Project in the recent regional assessment of groundwater quality in the glacial aquifer system (fig. 3). The second approach is to develop hydrogeologic settings across the study area that build on the study of stratified sand and gravel aquifers in the northeastern part of the study area (Randall, 2001; Kontis and others, 2004). In this approach, the glacial aquifer system will be subdivided into units with similar hydrogeology to allow for analysis of similar units across the system. This analysis will be used to contrast the effects of hydrogeology and climatic variation across the system on groundwater availability.

Background

Meinzer (1923) classified groundwater resources for the United States by physiographic regions and the age of the aquifer material. That work lays the groundwork for subsequent hydrogeologic frameworks used through the present day. Meinzer (1923) states the importance of Quaternary-age deposits and notes that glacial deposits are one of class of these deposits:

> The Quaternary is by far the important system in the United States with respect to water supply. Indeed, it would probably not be an exaggeration to say that it is as important as all other systems taken together. It lies at the surface throughout the largest area, supplies the most wells, and affords the greatest quantities of water.
>
> The Quaternary deposits of the United States are for the most part included in three groups—glacial drift [glacial deposits], the valley fill of the West, and the deposits of the Atlantic Coastal Plain. Both glacial drift and valley fill are of especial importance as sources of water, the drift being the principal source of ground water in the northern part of the country and the fill being the principal source in the western part.

Meinzer (1923) continues the discussion of glacial drift deposits by citing 84 reports written at the State level describing water resources within the glacial aquifer system; the importance of the glacial aquifer system to water supply was clearly recognized and described starting in the late 19th century.

The groundwater regions based on physiography and age (Meinzer, 1923) were merged and simplified into 10 regions by Thomas (1951). These 10 regions were subsequently used by McGuinness (1951, 1963) in summaries to Congress on groundwater conditions in the United States. The current study area is covered by 3 of the 10 regions: Western Mountain Ranges, Glaciated Central region, and Glaciated Appalachian region. Alaska was included in the State summary section of the 1963 report, but it was not assigned to a groundwater region (McGuinness, 1963).

Heath (1984) modified the work by Thomas (1951) and added Alluvial Valley, Southeast Coastal Plain, Hawaii, Alaska, and Puerto Rico and U.S. Virgin Islands to create 15 groundwater regions. Note that the glaciated and unglaciated Appalachian regions were included by Heath (1984) in the glaciated and unglaciated Central regions. The relevant regions for this framework report are the Western Mountain Ranges, Alluvial Basins, Glaciated Central region, Northeast and Superior Uplands, and Alaska. The addition of an Alluvial Valley region that includes deposits in the glaciated and nonglaciated parts of the United States highlights the importance of valley-fill deposits to water supply.

North America was later classified into 28 groundwater regions in part of a volume commemorating the "Decade of North American Geology" (Heath, 1988). Relevant summaries of glaciated areas in this volume include Farvolden and Cherry (1988), Krothe and Kempton (1988), Lennox and others (1988), Randall and others (1988), Rosenshein (1988), Sloan and van Everdingen (1988), and Stephenson and others (1988). Glacial deposits such as glacial alluvial and valley fill (for example, in buried bedrock valleys) were again noted as important features that could yield large amounts of groundwater to wells across the different regions. Other glacial features associated with aquifers that yield moderate to high volumes are ice-contact and outwash deposits (Stephenson and others, 1988). Tills and other poorly sorted deposits resulting from several depositional mechanisms are noted over glaciated parts of the continent. These deposits may be aquitards or locally important as capable of supplying low to moderate yields for domestic and, perhaps, agricultural supply, which depends on the presence of coarse material, poorly stratified lenses, weathering, or fractures (Meinzer, 1923; Heath, 1984; Stephenson and others, 1988).

The USGS initiated the RASA Program in 1978 to quantify groundwater resources within major aquifer systems (Sun and Johnston, 1994). Rather than attempting to study groundwater resources by the previously described groundwater regions, each of which could have several aquifers present and used in different parts of the region, the RASA Program was organized upon the study of major aquifer systems. The aquifer systems were "from two general types: (1) an aquifer system comprised of an extensive set of aquifers and confining units that may be discontinuous locally, but which act hydrologically as a single system on a regional scale; and (2) a system consisting of a set of independent aquifers that share many common characteristics hydrologically" (Sun and Johnston, 1994). These major aquifer systems became known as principal aquifers (Miller, 1999). Glacial-deposit aquifers are from the second type of major aquifer systems. The glacial aquifer system examined herein is formed from independent aquifers and low-permeability units comprised of unconsolidated deposits that share common origins across North America despite differences in climate or details of the specific local hydrogeologic conditions.

Hydrogeologic Framework Based on Aquifer Types and Hydrophysiographic Regions

One approach in developing a hydrologic framework for the study is to propose hydrophysiographic regions or settings built from idealized aquifer types or local hydrogeologic components for the study area. This approach is an extension of the previous work in the Northeastern United States (Kontis and others, 2004) and Southwestern United States (Anning and Konieczki, 2005). The approach is to group aquifer types defined at the local level into flow systems and ultimately define hydrophysiographic regions. The hydrophysiographic regions may be built from the local level or be the large regions from previous studies (for example, McGuinness, 1963; Heath, 1988). At the local and subregional scale, mapping and interpretation of the glacial geology would be necessary to develop base geology maps, identify aquifer types, and scale to hydrogeologic flow systems. Because of the size of the study area, new mapping will not be part of this study, and the geographic analysis will be used to develop the classification based on existing maps and reports.

Water-Well Record Analysis

To complement the analysis using existing geologic maps and analysis of hydrogeology in parts of the study area, the study takes advantage of recent availability of electronic water-well records in many States across the glacial aquifer system (Bayless and others, 2017). A USGS internal standardized database of water-well records assembled from individual State databases and data from USGS will inform three-dimensional analysis of the glacial aquifer system by providing information on lithology with depth. For inclusion in the internal database, water-well records meet location and several other broad quality-control checks. Several interpolated maps based on the data have been produced, such as total thickness of glacial deposits, total sand and gravel thickness, and estimated effective horizontal and vertical hydraulic conductivities based on literature values assigned to lithologic terms (Bayless and others, 2017). The internal water-well record database is one of the few available datasets that provide information on glacial deposits with depth. Because of the heterogeneous nature of these deposits, these data may prove very powerful in the development of numerical and statistical models of groundwater availability or groundwater quality.

Generalized Groundwater Budget Components

Generalized groundwater budgets will be estimated for the glacial aquifer system of the continental United States and the four NAWQA regions for the glacial aquifer system (excluding Alaska). The groundwater budgets alone do not provide enough information to determine groundwater availability because availability also depends on constraints; however, the groundwater budgets are necessary to build the analysis (Bredehoeft and others, 1982; Bredehoeft, 1997; Bredehoeft, 2002; Healy and others, 2007). These budgets can aid in future development of groundwater-flow models used to quantify the response of the groundwater budget in response to development or climate change. The system and regional budgets also set the context for discussing groundwater availability, and spatial variation in groundwater-flow budgets across the study area reveals the importance of climate differences across the system in determining regional and local groundwater availability.

Recharge and Discharge

An initial estimate of recharge and discharge for the glacial aquifer study area in the conterminous United States is made using the BFI and recharge grids developed by Wolock (2003a, b). These estimates are based on analysis at reference streamgages in the Geospatial Attributes of Gages for Evaluating Streamflow, version II (GAGES II) dataset (Falcone and others, 2010; Falcone, 2011) interpolated using inverse-distance weighting interpolation to a 1 kilometer (km)×1 km grid across the conterminous United States. Three issues arise with this estimate of recharge for the glacial aquifer system study: (1) whether the method used to perform base-flow separation at gages is consistent with other estimates, (2) whether the inverse-distance weighting interpolation of the discharge values at selected streamgages across the region used to indicate recharge satisfactorily reflects the distribution of recharge, and (3) whether long-term average recharge estimates can be improved by also considering the annual variation in recharge and providing this variability to users of the information. The first issue is addressed in this report, the other two issues require additional study.

The BFI method (Wahl and Wahl, 1995) was used to estimate base-flow index for the GAGES II dataset. Subsequent analysis from the literature with a synthetic watershed model indicated that this method may underestimate recharge (Partington and others, 2012). To assess BFI results in the study area, regional estimates of recharge computed for the Great Lakes Basin (Neff and others, 2005; Neff and others, 2006) using several methods were examined. The methods used were BFLOW (Arnold and Allen, 1999), PART (Rutledge, 1998), UKIH (Piggott and others, 2005), and HYSEP fixed-interval (HYSEP1), HYSEP sliding-interval (HYSEP2), and HYSEP local-minimum (HYSEP3) (Sloto and Crouse, 1996). For the Great Lakes estimates, the BFI, UKIH, and BFLOW methods produce similar results; the HYSEP3 estimates are intermediate between the BFI method and the estimates using the HYSEP1, HYSEP2, and PART methods with BFI estimating the lowest value of the five techniques (fig. 5); similar results are observed for the reference streamgages in the GAGES II dataset across the glacial aquifer system study area (fig. 6).

Given these results for the Great Lakes part of the study area, and despite inherent uncertainties associated with base-flow separation techniques (Dingman, 2002; Partington and others, 2012), the BFI-based estimate (Wolock 2003a, b) will be increased to produce estimates closer to the HYSEP local-minimum method (HYSEP3) (Sloto and Crouse, 1996). Graphing was used to compare BFI values using HYSEP3 method against BFI-method-derived values for streamgages in the Great Lakes Basin. Determining the best-fit line forced through zero yields a slope of 1.21 (fig. 7). The same approach using all annual BFI values at reference streamgages gives a slope of 1.19 (fig. 8), and using the period of analysis (1980–2013) for the 391 reference streamgages gives a slope of 1.21 (fig. 9). Based on these results, the BFI grid and

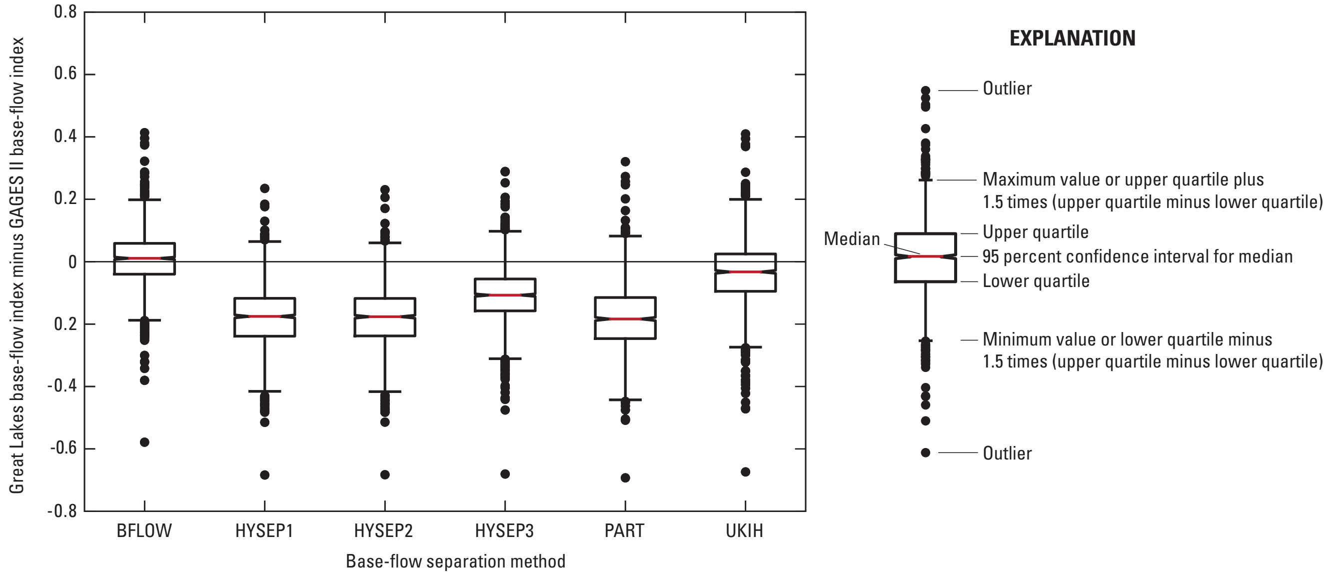


Figure 5. Difference between the estimated base-flow index (BFI) for various base-flow separation techniques for streamgages in the Great Lakes Basin (Neff and others, 2005) and BFI in the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES II) dataset (Falcone and others, 2010) determined using the BFI method. Negative values indicate that the other method produces a higher estimate of base flow than the BFI method used for GAGES II.

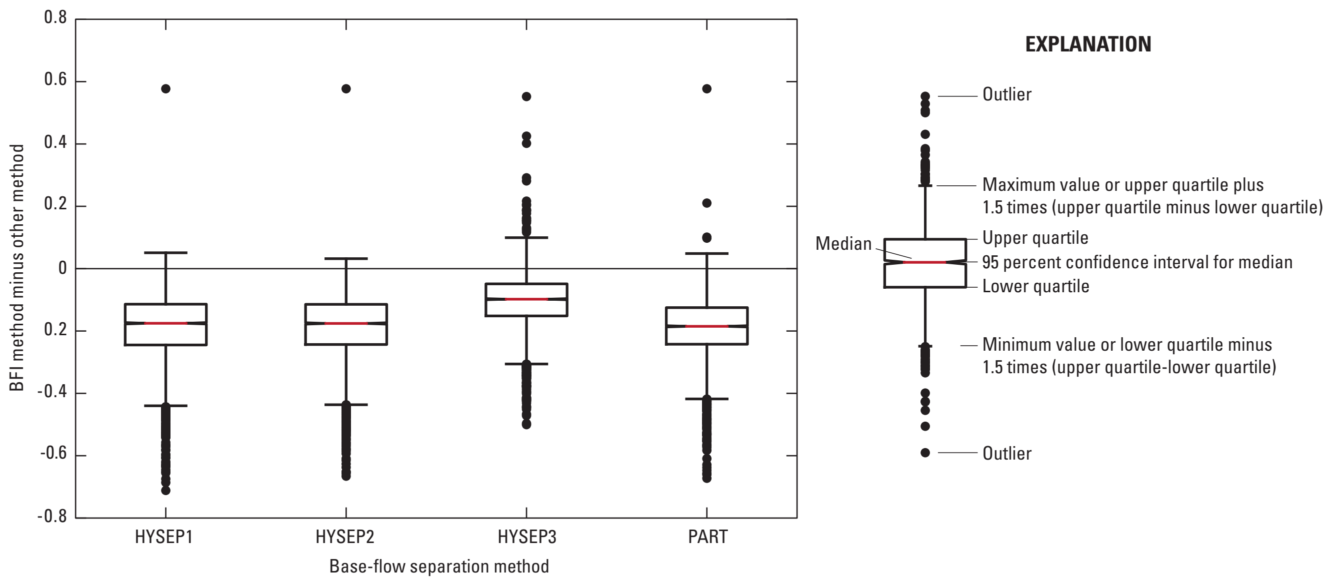


Figure 6. Difference between the estimated base-flow index (BFI) for various base-flow separation techniques and BFI determined using the BFI method for reference gages in the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES II) dataset (Falcone and others, 2010). Negative values indicate that the other method produces a higher estimate of base flow than the BFI method used for GAGES II. Each complete year of data at each reference gage is considered a separate observation in this boxplot.

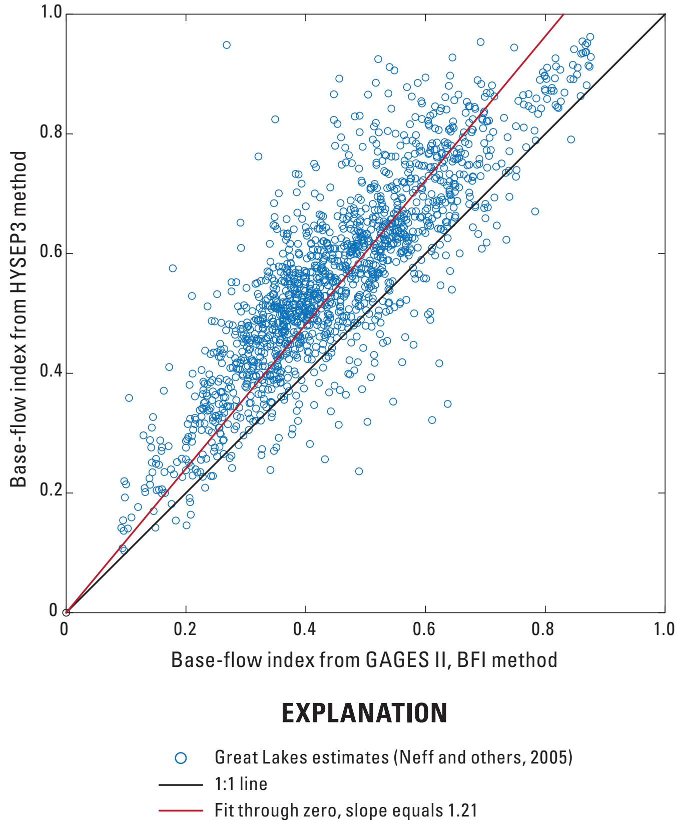


Figure 7. Base-flow index (BFI) computed using the HYSEP3 (local minimum) method plotted against the estimated BFI using the BFI method for streamgages in the Great Lakes Basin from the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES II) dataset.

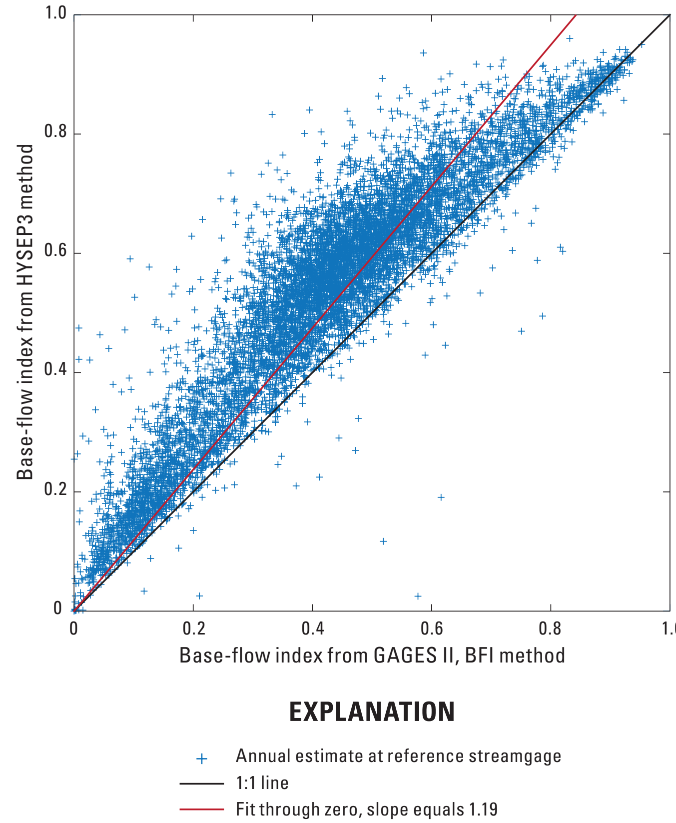


Figure 8. Base-flow index (BFI) computed using the HYSEP3 (local minimum) method plotted against the estimated BFI using the BFI method for 391 reference gages in the glacial aquifer study area from the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES II) dataset. Each point on the graph represents the BFI computed using a calendar year of data at a reference gage.

associated recharge estimate grid from Wolock (2003a, b) will be increased by a factor of 1.2 to estimate the recharge to the glacial aquifer system study area.

Water Withdrawals and Water Use

Water withdrawals from an aquifer system alter the groundwater budget. New withdrawals first remove water from storage as reflected in lowering of water levels in wells. After an initial period when all of the water produced by a well is from storage, the system transitions so that changes in recharge and discharge eventually balance the new withdrawal (Bredehoeft and others, 1982; Bredehoeft, 2002; Barlow and Leake, 2012). If the total change in recharge and discharge cannot balance the withdrawal, then groundwater in the system is being mined and long-term production from the well is not sustainable. Groundwater-flow modeling is required to quantify the rate that the system responds to new pumping and the magnitudes of changes in storage, discharge, and recharge (Bredehoeft, 2002); understanding withdrawals imposed on the aquifer system and the observed response of the system to these withdrawals are crucial in developing a groundwater-flow model. In addition, estimates of water withdrawals are needed to complete the groundwater budget for a region with production wells, and, in some areas, water withdrawals may be a significant part of the groundwater budget (Healy and others, 2007; Faunt, 2009).

Estimation of groundwater withdrawals from the glacial aquifer system is confounded by lack of information on the source aquifer of reported groundwater use. In parts of the system, the bedrock aquifers underlying the glacial aquifer system are important for water supply, and the distribution of withdrawals between different aquifers may not be known. In some areas, however, the distribution among aquifers can be quantified. For example, water use by source aquifer was estimated for a groundwater flow model of the Lake Michigan Basin (Buchwald and others, 2010); in that study, approximately 55 percent of the groundwater withdrawals for the 2001–5 period were attributed to the glacial aquifer system (fig. 10). To estimate water withdrawals from the glacial aquifer system, a nationwide study disaggregating groundwater withdrawals by principal aquifer for calendar year 2000 (Maupin and Barber, 2005) may be used to estimate water

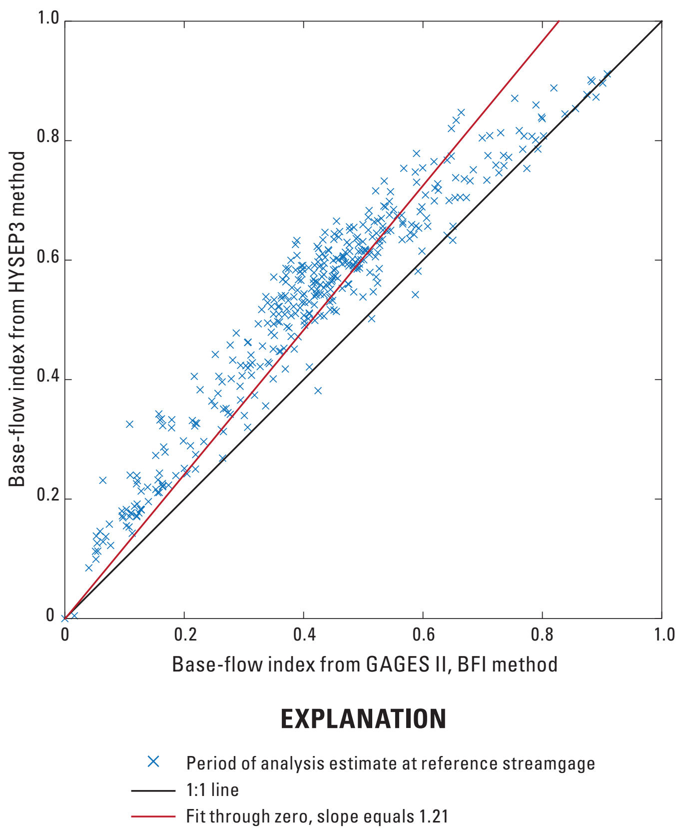


Figure 9. Base-flow index (BFI) computed using the HYSEP3 (local minimum) method plotted against the estimated BFI using the BFI method for 391 reference gages in the glacial aquifer system study area from the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES II) dataset. Each point on the graph represents the period of analysis estimate of BFI at a reference gage using records with at least 1 calendar year of data in the period from 1980–2013.

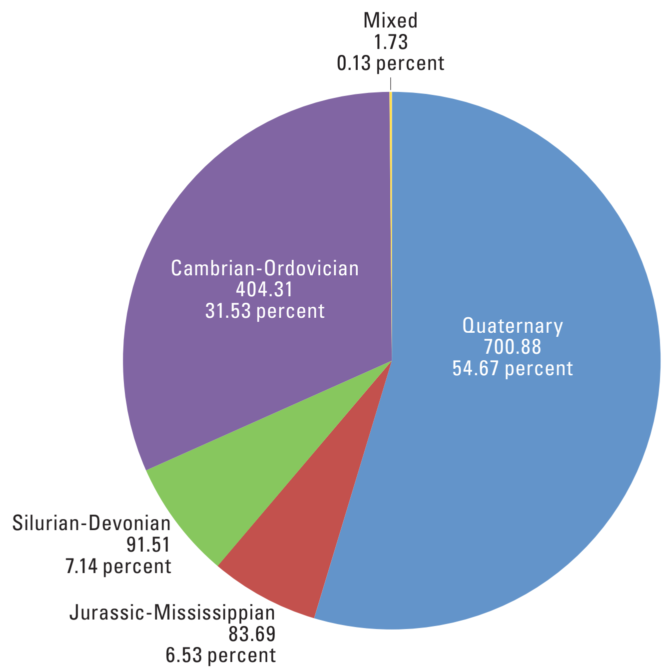


Figure 10. Distribution of estimated groundwater withdrawals in million gallons per day from source aquifers in the Lake Michigan Basin groundwater-flow model, 2001–5, data from appendix 2 of Buchwald and others (2010). Quaternary indicates the glacial aquifer system.

withdrawals from the glacial aquifer system for 2005 and 2010. For each State in the glacial aquifer system, the ratio of estimated withdrawals from the glacial aquifer system to total groundwater withdrawals in the part of the State in the glacial aquifer system was estimated using information from Hutson and others (2004) and Maupin and Barber (2005). These State ratios were then applied to estimated withdrawals by county, or the part of the county, in the glacial aquifer system for 2005 (Kenny and others, 2009) and 2010 (Maupin and others, 2014) to produce consistent estimates of withdrawals from the glacial aquifer system across the study area.

Storage

The final component of the groundwater budget to be estimated is the groundwater in storage in the system. Groundwater is a major freshwater reservoir; in fact, groundwater may be the only reasonable reservoir in many places. Groundwater storage can mitigate the effects of seasonal changes in rainfall or moderate droughts that would affect riverine or surface-water reservoirs by providing a stable source of water for various uses. Total storage estimates, however, do not reflect the available groundwater in the system (Alley, 2007): (1) not all the water in storage can be feasibly accessed, (2) changes in storage can affect other users, (3) changes in storage can induce flow from adjacent aquifers and lead to deleterious water-quality changes, and (4) even relatively small changes in storage can affect surface-water flows by decreasing discharge from the aquifer or inducing recharge from surface water to the aquifer (Kraft and others, 2012). The stable and accessible supply offered by groundwater has led to overexploitation in some areas around the world where groundwater levels have been reduced beyond the ability of the system to meet demands (Schwartz and Ibaraki, 2011); therefore, change in storage with time is an important feature of the flow system to consider. Literature values for storage coefficients will be used with mapped glacial thicknesses to estimate patterns of groundwater in storage across the study area. Reported water-level information from monitoring wells (Bartolino and Cunningham, 2003; Coon and Sheets, 2006), areas of agricultural drainage (Konikow, 2013), and Gravity Recovery And Climate Experiment (GRACE) satellite data (Huang and others, 2012) will be explored to estimate the change in storage in the system.

For the United States part of the Great Lakes Basin, storage in the glacial aquifer system was estimated to be on the order of 580 cubic miles (mi^3) (8.6×10^{13} cubic feet), approximately the volume of a sixth Great Lake of storage (Coon and Sheets, 2006). This estimate only considered aquifer units and did not account for storage in tills or other low-permeability deposits. A similar approach was adopted in this study using thickness and distribution of surficial units from Soller and others (2011) for the part of the system east of the Rocky Mountains. This base map (Soller and others, 2011) was used rather than the "Quaternary Geologic Atlas of the United States" (U.S. Geological Survey and others, 2013), hereafter referred to as the Quaternary geologic atlas, because it has estimated thicknesses; although, note that use of this map limits the estimate of storage to the part of the study area east of the Rocky Mountains. Use of this base map was tested by repeating the estimate of Coon and Sheets (2006) for the United States part of the Great Lakes Basin.

Aquifer storage for unconfined aquifers including specific yield, storage release by drainage of the pore space in the aquifer material, and specific storage, storage release by the expansion of water and compression of the aquifer matrix, was estimated by Coon and Sheets (2006) using:

$$V_t=(S_y+hS_s)Ah=[S_y Ah]+[S_s Ah^2] \quad (1)$$

where,

- V_t is total volume of groundwater in storage, in cubic feet,
- S_y is specific yield of aquifer, dimensionless,
- h is saturated thickness of aquifer, in feet,
- S_s is specific storage of aquifer, per foot, and
- A is area of aquifer, in square feet.

Hydrogeologic Framework and Groundwater Budget

Despite a wealth of local studies and information (Wiltshire and others, 1986; Kahle and Futornick, 2012), integration of information into a comprehensive hydrogeologic framework for the study area proved to be very difficult; the foundational information is not available uniformly across the study area and analysis of existing information required a simpler approach. In particular, regional studies and maps tend to be available for the part of the study area east of the Rocky Mountains (Kontis and others, 2004; Soller and others, 2011; U.S. Geological Survey and others, 2013), whereas glacial aquifer studies west of the Rocky Mountains, including Alaska, tend to be local in scope (Kahle and others, 2011; Callegary and others, 2013). Because of data limitations, the hydrologic framework discussion focuses on the study area east of the Rocky Mountains. The two approaches outlined for hydrogeologic frameworks are developed, and groundwater budgets for each framework are discussed.

Generalized Hydrogeologic Frameworks

The development of a framework based on the type of aquifer and the geographic area relies on the aggregation of local-scale mapping. For the glacial aquifer system, State aquifer maps serve as an intermediate scale, and differences in aquifer mapping between States prevented development of a full aquifer-type hierarchy for the study area. In order to assemble a generalized hydrogeologic framework, maps available from the Quaternary geologic atlas (U.S. Geological Survey and others, 2013) were evaluated against previously published State and regional aquifer maps. The Quaternary geologic atlas coverage at the time of the study was only for the part of the study area east of the Rocky Mountains (U.S. Geological Survey and others, 2013). The resulting framework focuses attention on deposits that are likely to be dominated by sand and gravel and serve as aquifers. The second approach is based on NAWQA regions, which produces a more regional focus on the entire aquifer system and accounts for local aquifers. Important differences between State aquifer maps and the generalized frameworks are identified.

Hydrogeologic Framework Based on the Quaternary Geologic Atlas

To test the use of the Quaternary geologic atlas as a base map for the hydrogeologic framework, the map units found on the quadrangles that intersected the glacial aquifer system study area were classified into broad categories and converted from polygons to grids. The categories are generalizations of those used by Fullerton and others (2004) and are valley fill; outwash; ice contact; till; lacustrine coarse; lacustrine fine; loess or other eolian; peat, muck, and mud; other sand; other nonaquifer; alluvial fines; colluvium coarse; colluvium fine; bedrock; and water. These broad categories were further assigned as potential aquifer (valley fill, outwash, ice contact, lacustrine coarse, other sand), nonaquifer (till; lacustrine fine; peat, muck, and mud; loess or other eolian), or other nonaquifer (bedrock, alluvial fines, colluvium fine, colluvium coarse, water). Aquifer maps from the Northeastern United States, Minnesota, and North Dakota were then converted to grids. The degree to which the Quaternary geologic atlas captured the aquifer distribution was determined by the overlap between the gridded atlas categories and the gridded aquifer maps.

The regional stratified-drift aquifer map (Kontis and others, 2004) has six categories (fig. 11), and the map of potential aquifer material from the Quaternary geologic atlas appears to visually match the distribution of these units (fig. 12). Qualitatively, the potential aquifer material map lacks some of the smaller features mapped by the 1:500,000-scale map by Kontis and others (2004). Examination of these features shows that the geologic deposits related to these units are not delineated on the 1:1,000,000-scale Quaternary atlas. Quantitative comparison of the two maps is summarized in tables 2 and 3.

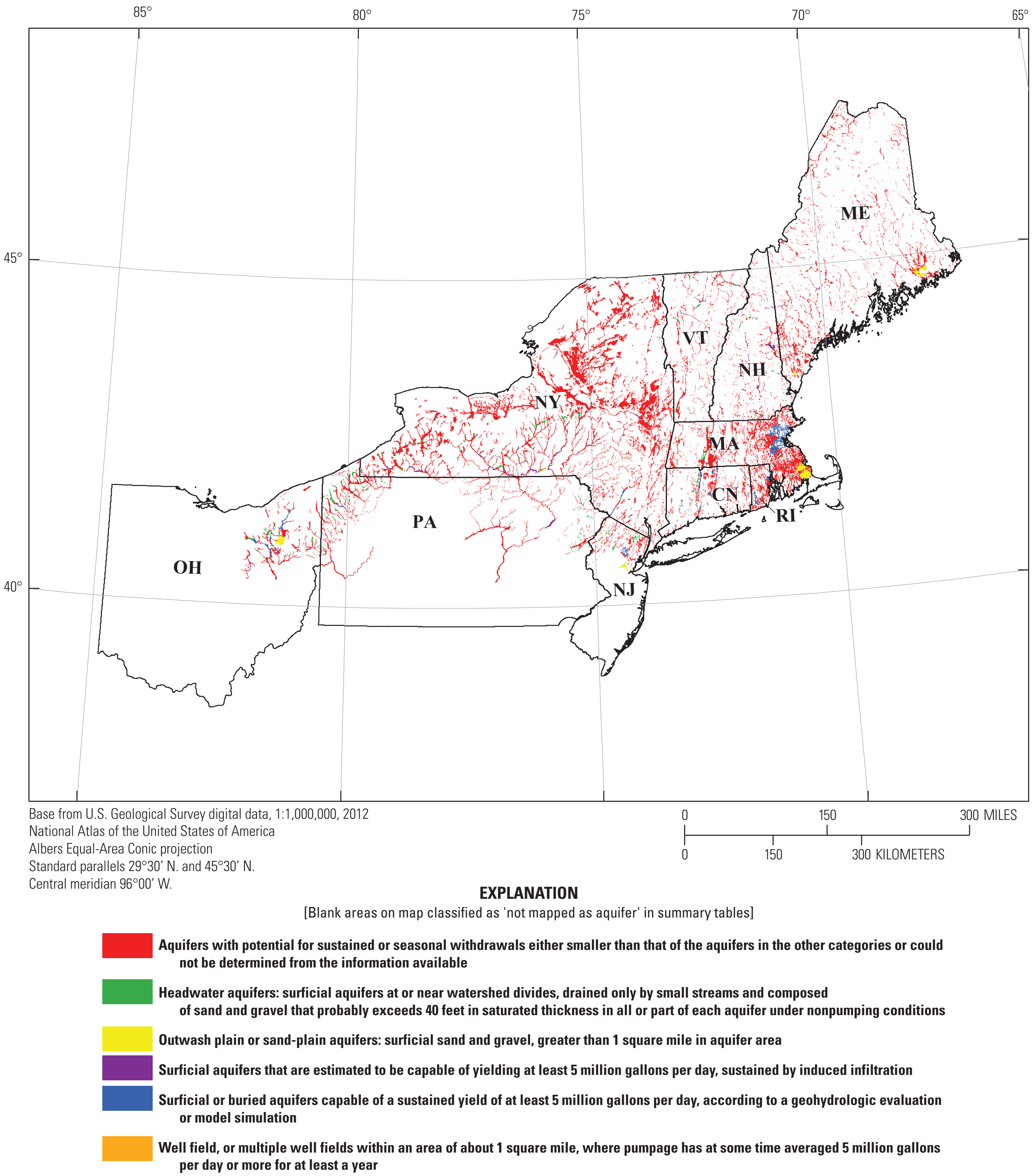


Figure 11. Stratified sand and gravel aquifers in the Northeastern United States (from Kontis and others, 2004).

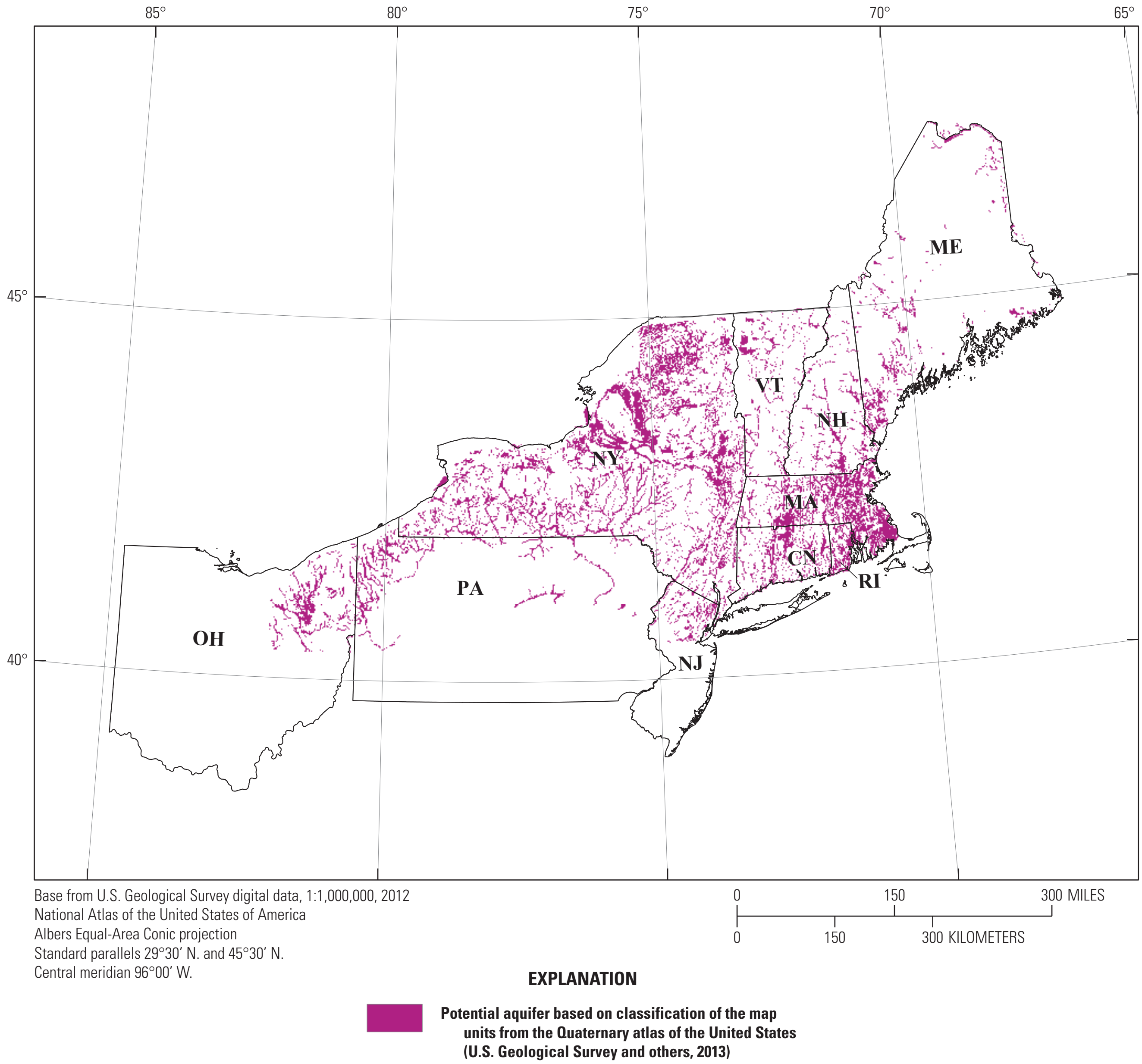


Figure 12. Potential aquifer material based on classified map units of Quaternary geologic atlas (U.S. Geological Survey and others, 2013).

Table 2. Quantitative comparison of Quaternary geologic atlas (U.S. Geological Survey and others, 2013) classification to stratified sand and gravel aquifers in the Northeastern United States (Kontis and others, 2004).

[Mgal/d, million gallons per day]

Quaternary geologic atlas classification	Well field yielding at least 5 Mgal/d at some time	Percent of mapped grid cells in each aquifer category					
		Surficial aquifer	Modeled aquifer	Unknown yield	Headwater	Outwash	Nonaquifer
Not a potential aquifer	0.005	0.07	0.17	5.4	0.2	0.04	94.1
Potential aquifer	0.14	1.2	1.8	37.9	1.6	1.3	56

Table 3. Quantitative comparison of stratified sand and gravel aquifer types of the Northeastern United States (Kontis and others, 2004) to classified mapped units in the Quaternary geologic atlas (U.S. Geological Survey and others, 2013).

Stratified sand and gravel aquifers in the Northeastern United States	Percent of mapped grid cells in each map unit category of the Quaternary geologic atlas												
	Valley fill	Outwash	Ice contact	Till	Lacustrine coarse	Lacustrine fine	Peat, muck, mud	Other sand	Other nonaquifer	Alluvial fine	Colluvium coarse	Colluvium fine	Water
Well field, or multiple well fields within an area of about 1 square mile, where pumpage has at some time averaged 5 million gallons per day or more for at least a year	30.6	28.2	17.8	7.4	3.7	4.5	1.7	0	2.3	0	0	0	3.8
Surficial aquifers that are estimated to be capable of yielding at least 5 million gallons per day, sustained by induced infiltration	28	22.2	18	16	4.8	6.3	0	0	1.8	0	0	0	3.6
Surficial or buried aquifers capable of a sustained yield of at least 5 million gallons per day, according to a geohydrologic evaluation or model simulation	4.3	9.1	43.5	23.2	5.7	7.6	1.4	0.4	1.5	0	0	0	3.1
Headwater aquifers: surficial aquifers at or near watershed divides, drained only by small streams and composed of sand and gravel that probably exceeds 40 feet in saturated thickness in all or part of each aquifer under nonpumping conditions	2.9	24.7	27.1	32.9	4.9	3.7	0.9	0	1.6	0	0	0.2	0.8
Outwash plain or large sand-plain aquifers: surficial sand and gravel, greater than 1 square mile in aquifer area	1	27	50	13.3	3.4	2.3	0	0.1	0.1	0.1	0	0	2.6
Aquifers whose potential for sustained or seasonal withdrawals is smaller than that of aquifers in the categories above or could not be determined from the available information	9	9	24	33	11	7.5	0.9	0.9	1.1	0	0	0.3	1.8

Examination of the tables indicates that the Quaternary geologic atlas classification captures the nonaquifer part of the map. The surficial geology in the region is dominated by sandy till, which is classified as a "nonaquifer," and 94 percent of the cells classified as "nonaquifer" in the Quaternary atlas are not mapped as aquifer material in the stratified sand and gravel aquifer map. Only about 5 percent of the material classified as "nonaquifer" are mapped as a potential aquifer in the stratified sand and gravel map, and the mismatch is almost all for areas mapped with unknown yield. Focusing on the material classified as "potential aquifer" indicates more mismatch, just over half of the cells classified as "potential aquifer" material are not mapped in the stratified sand and gravel map. Some of the mismatch may be attributed to differences in map scales and details in shape of mapped units. Overall, the Quaternary geologic atlas seems to capture the essential features of the stratified sand and gravel aquifer map, although on a more regional scale. The advantage of using the Quaternary geologic atlas as a base map for the glacial aquifer system study as opposed to the stratified sand and gravel aquifer map is that it extends across more of the study area.

A similar comparison may be made to the State Quaternary hydrogeology map for Minnesota (Land Management Information Center and others, 2000). The Minnesota map was selected as an example because the classification of aquifers is fairly simple and has four classes: outwash, alluvium, lake deposits, and nonaquifer. Each of these classes is further subdivided by estimated yield, but these subdivisions are not considered in the comparison. Examination of the State Quaternary hydrogeology map (fig. 13) and map units classified as “potential aquifers” from the Quaternary geologic atlas (fig. 14) indicates correspondence similar to the stratified sand and gravel aquifers map. In this case, the units on the State map (fig. 13) tend to be a bit larger and more uniform compared to the corresponding units from the Quaternary geologic atlas (fig. 14). The State map also has a denser network of alluvial aquifers, especially in southern Minnesota.

The overlap between gridded maps of Minnesota is similar to the results from the northeastern stratified-drift aquifer. Mapped units on the Quaternary geologic atlas that are classified predominately as “not a potential aquifer,” 91.4 percent, overlap cells classified on the Minnesota Quaternary hydrology geology map as “nonaquifer” (table 4). Some cells in the “not a potential aquifer” class overlap with alluvium, and this mismatch is related to the denser network of alluvium cells in southern Minnesota (fig. 14.) Examination of the comparison from the distribution within categories from the Minnesota Quaternary hydrogeology map (table 5) indicates that mapped units from the Quaternary geologic atlas classified as “valley fill” correspond quite well to the alluvium category on the Minnesota map, valley-fill cells are less than 1 percent of the other hydrogeologic categories. Till is the dominant classification for mapped units from the Quaternary geologic atlas, and till cells appear as a substantial percentage of cells in all aquifer categories. This mismatch is a reflection of the more irregular potential aquifer shapes on the Quaternary geologic atlas compared to the more regular shapes on the hydrogeology map. The mismatch also is caused by some areas where the hydrogeology map indicates an outwash aquifer but the Quaternary geologic atlas indicates till. One explanation for this discrepancy is that the surficial materials may be till but may overlie an outwash aquifer. In this case, the use of the Quaternary geologic atlas as a base map will miss some aquifers. The importance of potentially buried aquifers is explored in more detail in the last comparison between a State aquifer map and the Quaternary geologic atlas.

In contrast to the four-category Minnesota Quaternary hydrogeology map, the North Dakota surficial aquifer map (North Dakota State Water Commission, 2010) has 278 mapped aquifers at 1:100,000-scale (fig. 15). North Dakota was selected as an example because of the Spiritwood aquifer complex, a large buried-valley complex (Winter and others, 1984; Kehew and Boettger, 1986), represented on the State map that is not well identified through classification of the map units on the Quaternary geologic atlas (U.S. Geological Survey and others, 2013). The Spiritwood aquifer complex (figs. 15–17) includes the following aquifers from the North Dakota surficial aquifers map: Spiritwood, Spiritwood-Barnes, Spiritwood-Berlin, Spiritwood-Devils Lake, Spiritwood-Grand Rapids, Spiritwood-Griggs, Spiritwood-LaMoure SE, Spiritwood-Oakes, Spiritwood-Sheyenne River, Spiritwood-Stutsman, and Spiritwood-Warwick. The mapped units of the Quaternary geologic atlas classified as potential aquifers show good correspondence to the North Dakota surficial aquifer map in several places (fig. 16), but the Spiritwood aquifer complex is notably missing in the potential aquifer map derived from the Quaternary geologic atlas. This aquifer is described as being the result of catastrophic drainage of glacial lakes eroding sediments and bedrock and subsequent filling by permeable sediments that can be overlain in areas by lake deposits and glacial till (Kehew and Boettger, 1986; Hobbs and Bluemle, 1987).

The inability of the classified map units from the Quaternary geologic atlas to identify the Spiritwood aquifer complex motivates application of methods to use digital water-well records to provide information with depth across the study area that can help identify these buried features on a regional scale. By analyzing water-well driller records in electronic databases compiled by States (see “Water-Well Record Analysis” section), insight into the distribution of glacial materials with depth can be obtained. For the glacial aquifer system study, the key steps in the analysis are (1) broad quality-control tests to eliminate records that are obviously mislocated or have errors in reported altitude, well depth, or lithology; (2) translation of lithologic terms reported on the various water-well records to a consistent set of terms; and (3) assignment of representative values for coarse materials or textbook hydraulic conductivity values used to estimate the percentage of coarse material or estimated effective hydraulic conductivity for the layered system (Arihood, 2009; Bayless and others, 2017). For the North Dakota example, interpretation of reported lithologies from water-well records into sand and gravel thickness identifies much of the mapped Spiritwood aquifer complex (fig. 17). Patterns of thicker sand and gravel deposits, in a general way, match other mapped aquifers, but some mapped units are not identified, and in some areas, the distribution of sand and gravel appears to be larger than the mapped units.

Despite complications from buried systems, the classified map derived from the Quaternary geologic atlas will be used as one of the hydrogeologic frameworks for part of this study area (figs. 18 and 19). For analysis within the system, sand and gravel thickness or other interpreted maps based on water-well records will augment the Quaternary geologic atlas framework by providing information on the distribution of aquifer material with depth (fig. 20). The water-well records analysis is not used as the primary data source for the hydrogeologic framework for several reasons: (1) in areas with sparse data, the resulting framework is not helpful, (2) some features are missing in the water-well records because only recent information is included in some State databases and older water-well records that could indicate the presence of aquifers are not included in the analysis, and (3) water-well records were not available in electronic format suitable for this analysis for several of the States in the study area (Bayless and others, 2017). This framework focuses attention on the glacial aquifer system in a way similar to that used by Kontis and others (2004) and Miller (1999).

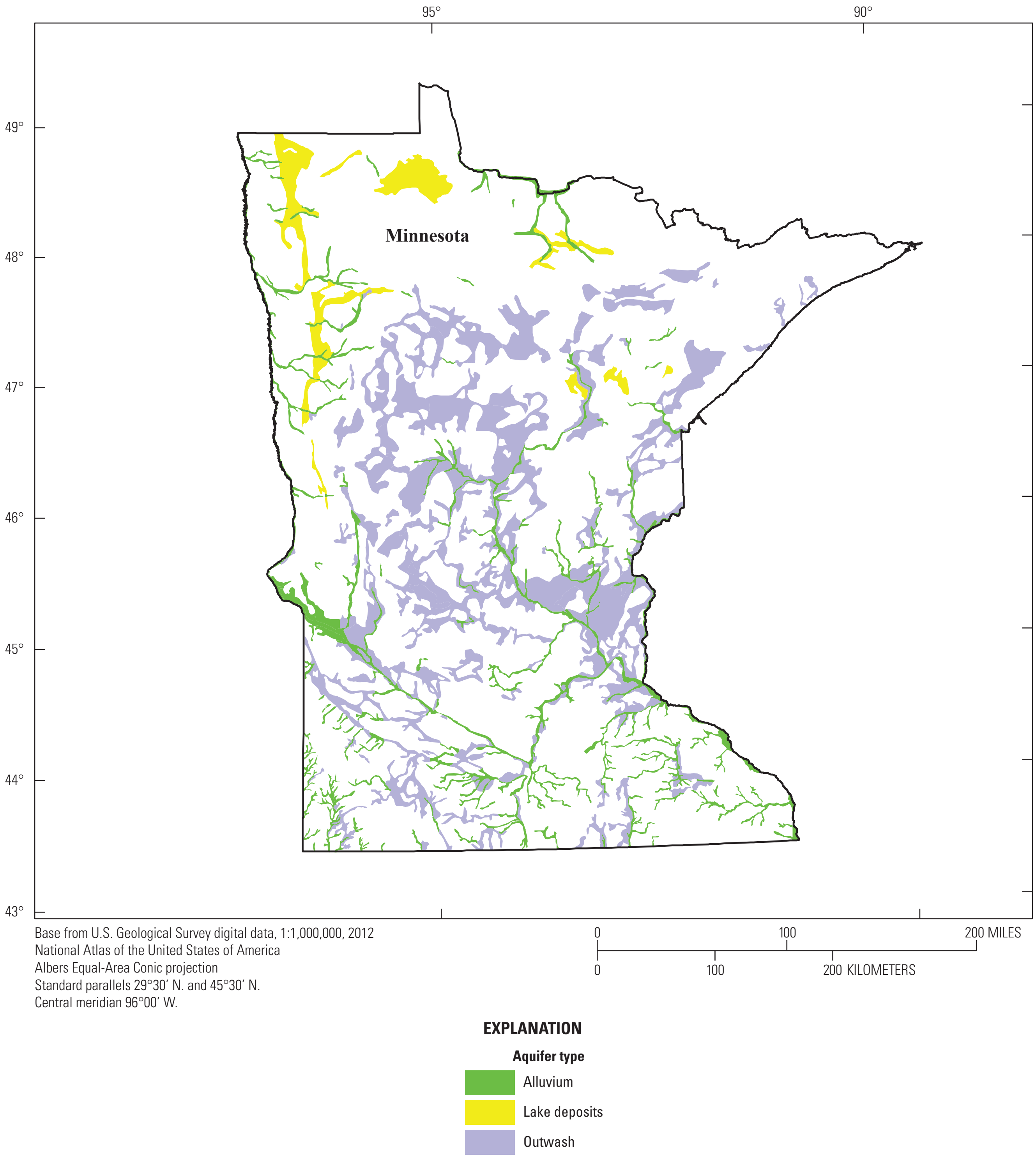


Figure 13. Minnesota Quaternary hydrogeology indicating three major aquifer types: alluvium, lake deposits, and outwash (Land Management Information Center and others, 2000).

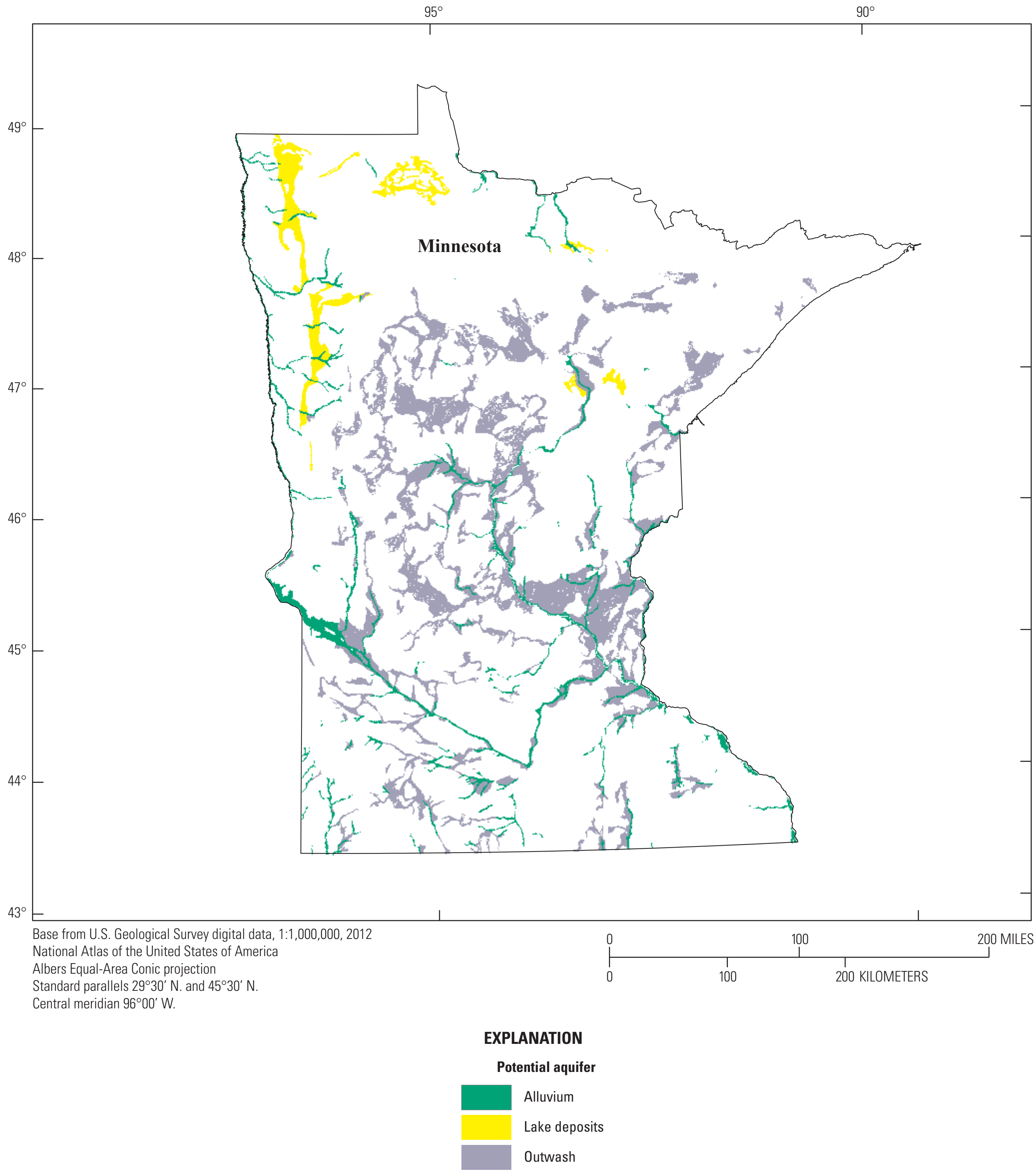


Figure 14. Potential aquifer material based on classified map units for potential aquifer from the Quaternary geologic atlas (U.S. Geological Survey and others, 2013). The map units are shaded by the underlying aquifer types from the Minnesota Quaternary hydrogeology map (Land Management Information Center and others, 2000).

Table 4. Quantitative comparison of Quaternary geologic atlas (U.S. Geological Survey and others, 2013) classification to the Minnesota Quaternary hydrogeology map (Land Management Information Center and others, 2000).

Quaternary geologic atlas classification	Percent of mapped grid cells in each category from the Minnesota Quaternary hydrogeology map			
	Alluvium	Lake deposits	Outwash	Nonaquifer
Not a potential aquifer	2.9	1.0	4.7	91.4
Potential aquifer	13.1	7.1	47.1	32.3

Hydrogeologic Framework Based on National Water-Quality Assessment Regions

The four regions used by the NAWQA glacial principal aquifer study (fig. 3) were used by Warner and Ayotte (2014) to discuss observed differences in water quality. The characteristics of these regions are summarized in table 1. These regions focus on the entire aquifer system and serve as a contrasting framework to that based on the Quaternary geologic atlas, which describes the mapped units with highest potential to serve as productive aquifers.

Summary of Hydrogeologic Frameworks

The two hydrogeologic frameworks (1) based on classified map units from the Quaternary geologic atlas (U.S. Geological Survey and others, 2013) and (2) use of four NAWQA regions (Warner and Ayotte, 2014) represent contrasting views of the study area. The classified map units focus attention on large surficial deposits that are more likely to act as aquifers and support larger capacity wells; however, this approach has been shown to miss important buried aquifers formed by glacial processes and likely misses local aquifers that can support municipal, irrigation, or industrial wells that are not mapped at the 1:1,000,000-scale or result from local-scale heterogeneities within a regional depositional environment that is not expected to support wells with moderate to large yields. The focused approach also does not recognize that many low-yield domestic wells are located in areas designated as nonaquifer, and that the nonaquifer material may be important for groundwater storage or may provide base flow to streams. Conversely, the regional (NAWQA) approach recognizes that wells are placed in many areas of the glaciated part of North America that would not be considered aquifers from a public water supply perspective. This leads to inconsistencies in terminology because till or other low yield units are considered to be part of the aquifer system. Groundwater/surface-water interaction also may be highest in areas mapped as potential aquifers in the classification approach and not as important in nonaquifer parts of the regional approach. These two approaches will be retained in the study as each is appropriate for different groundwater availability questions. For example, base-flow and recharge estimates typically are made by looking at watershed characteristics and not restricted to classified map units. In developing groundwater-flow models to study groundwater availability, either framework will have to be augmented with depth-dependent information, from water-well records for example, and with local to statewide studies and maps.

Generalized Groundwater Budget

Generalized groundwater-budget components are estimated using existing data for the glacial aquifer system study area in the conterminous United States. The components are further subdivided into the four NAWQA regions (East, Central, West-Central, and West) to highlight variation in climate across the study area.

Table 5. Quantitative comparison of Minnesota Quaternary hydrogeology map (Land Management Information Center and others, 2000) to classified mapped units in the Quaternary geologic atlas (U.S. Geological Survey and others, 2013).

Minnesota Quaternary hydrogeology map	Percent of mapped grid cells in each category in the Quaternary geologic atlas												
	Valley fill	Outwash	Ice-contact	Till	Lacustrine coarse	Lacustrine fine	Peat, muck, mud	Other sand	Other nonaquifer	Alluvial fines	Colluvium coarse	Colluvium fine	Water
Alluvium	20.2	31.9	0.1	26.3	4.2	7.8	0.9	0	0	0	4.1	0	4.6
Lake deposits	0.5	0.2	0	6.5	68.1	4.6	18.8	0	0	0	0	0	1.2
Outwash	0.8	65.3	0	19.8	4.7	1.1	1.3	0	0.1	0	0.2	0	6.7
Nonaquifer	0.5	5.4	0	66.7	3.1	8.7	7.5	0	0.2	0	3	0	4.9

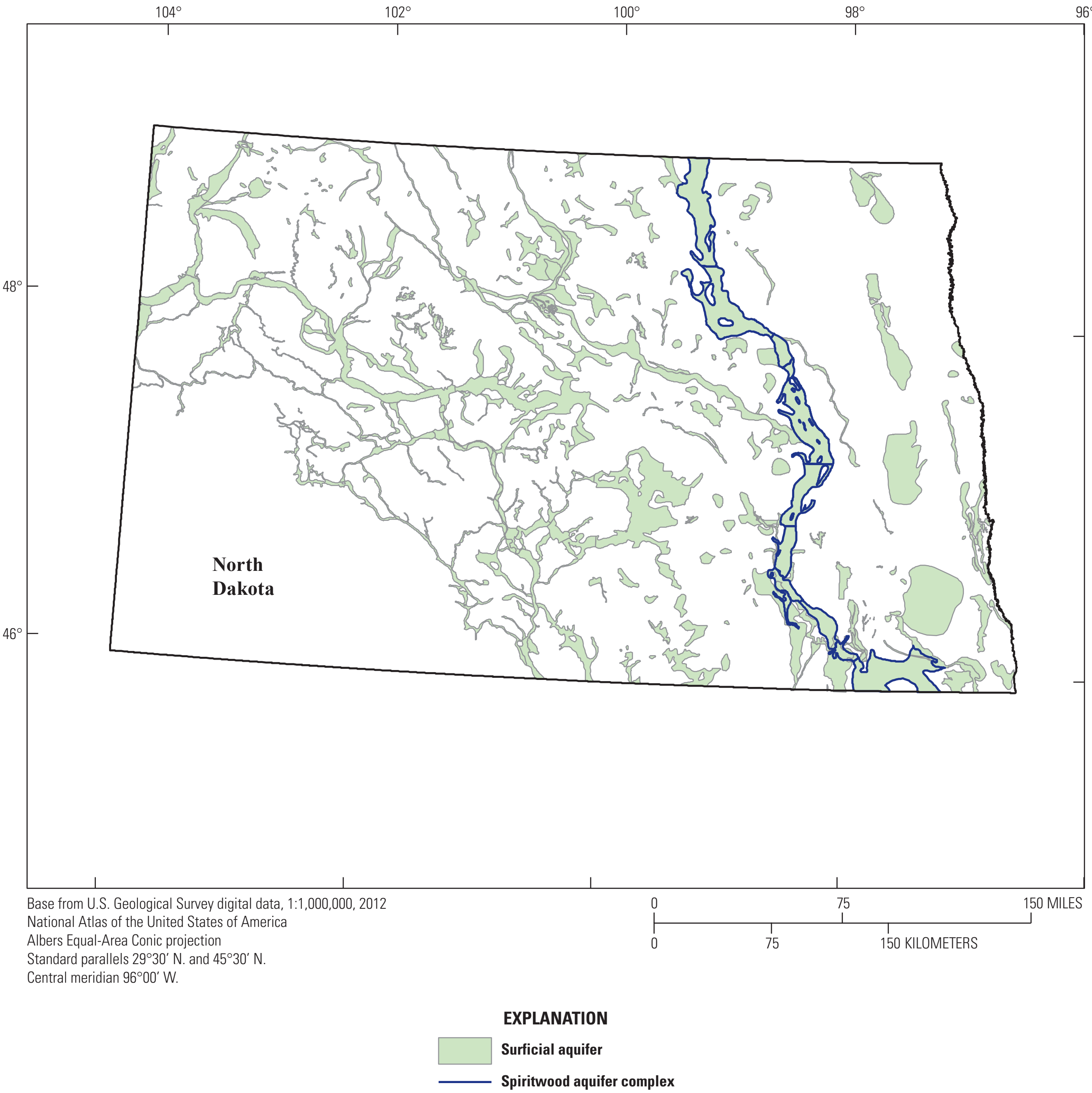
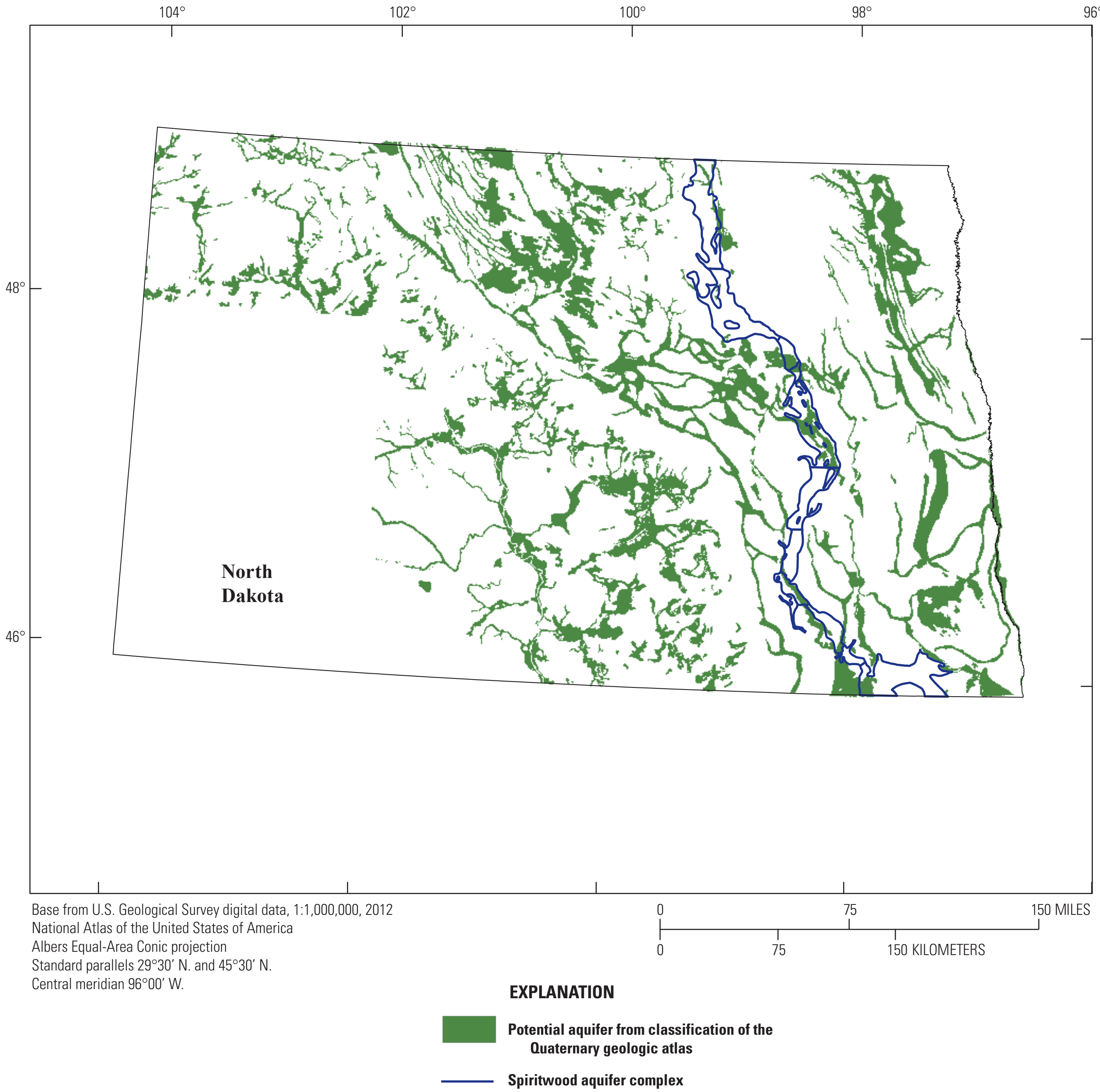


Figure 15. North Dakota surficial aquifers map (North Dakota State Water Commission, 2010).



Base from U.S. Geological Survey digital data, 1:1,000,000, 2012
National Atlas of the United States of America
Albers Equal-Area Conic projection
Standard parallels 29°30′ N. and 45°30′ N.
Central meridian 96°00′ W.

Figure 16. Potential aquifer material based on classified map units of Quaternary geologic atlas (U.S. Geological Survey and others, 2013).

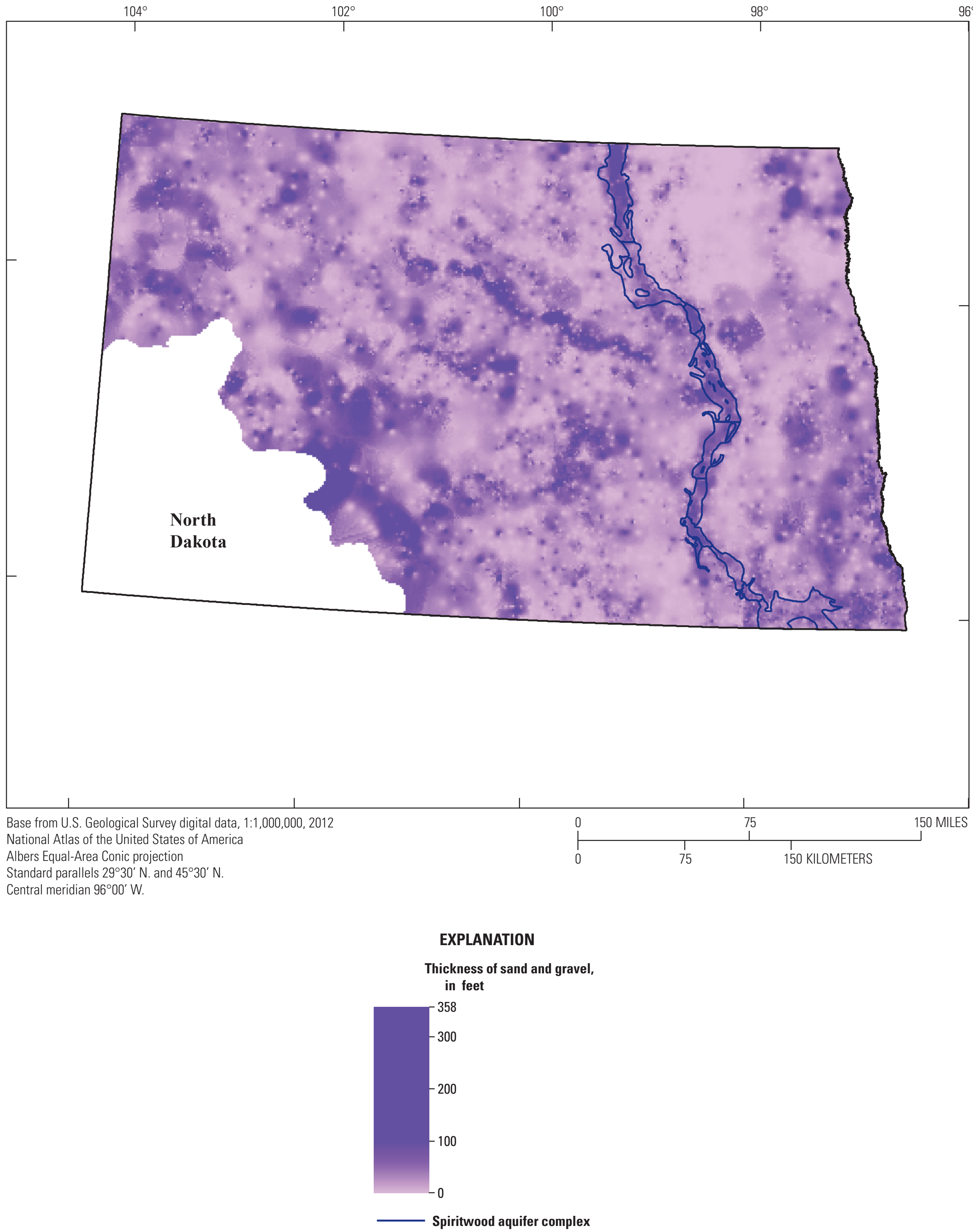


Figure 17. Estimated sand and gravel thickness for North Dakota from interpolation of water-well records using methods described by Arihood (2009) and Bayless and others (2017).

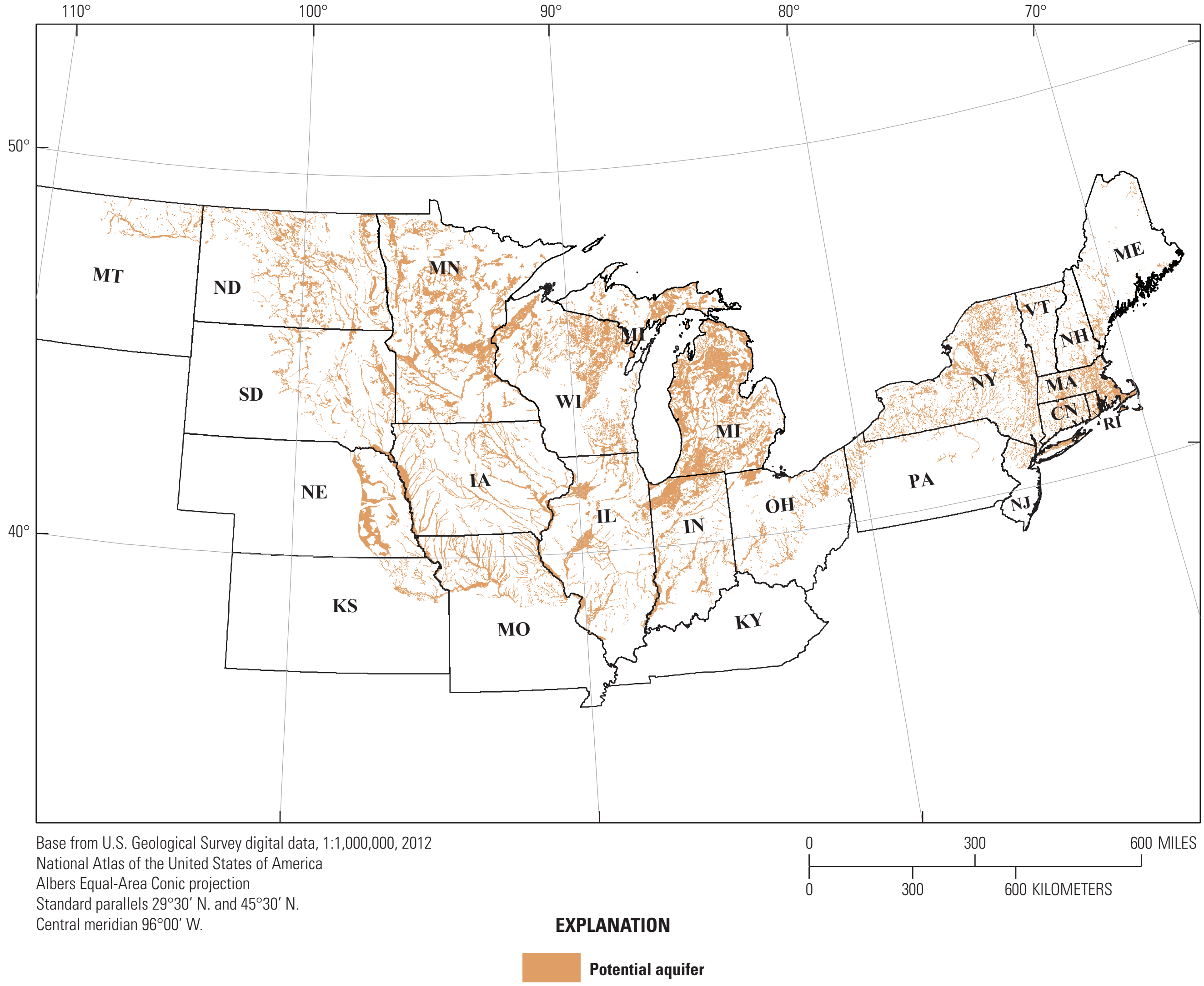


Figure 18. Hydrogeologic framework for the glacial aquifer system study based on classification of mapped units derived from the Quaternary geologic atlas (U.S. Geological Survey and others, 2013) grouped to show potential aquifer material.

Recharge and Discharge

The large size of the study area leads to a groundwater budget that is dominated by natural recharge and discharge. Traditionally, these two budget components are estimated by considering the long-term change in storage in the system to be negligible thereby assuming that long-term average recharge is equal to long-term average discharge. For the glacial aquifer system, the assumption that long-term change in storage is negligible is reasonable because groundwater-level data across the study area do not indicate long-term declines in water levels (Bartolino and Cunningham, 2003; Konikow, 2013, 2015). Long-term discharge is typically estimated using streamgage records. Records are analyzed to separate the base-flow component of streamflow from the runoff component. By analyzing several years of records with multiple storm events, the average long-term base flow from aquifer systems to streams may be derived (Gebert and others, 2007). This base-flow estimate may be directly used to represent long-term discharge, and thus recharge, or it may be augmented by modeling (Arnold and others, 2000) and water-quality information (Nolan and others, 2007; Gates and others, 2014) to make an estimate of recharge.

Recharge estimates for regional studies are challenging because recharge depends on local processes that differ across the region and because of the variety of methods that may be used to estimate recharge (Delin and others, 2007; Gebert and others, 2007). Regionalized methods produce spatially smoothed estimates, and local methods produce estimates with much more spatial variability. The processes controlling local recharge are expected to vary across the study area depending on the hydrogeologic setting. Consider the stratified sand and gravel aquifers in the Northeastern United States that typically are in valley-fill settings (fig. 21). Net recharge to these

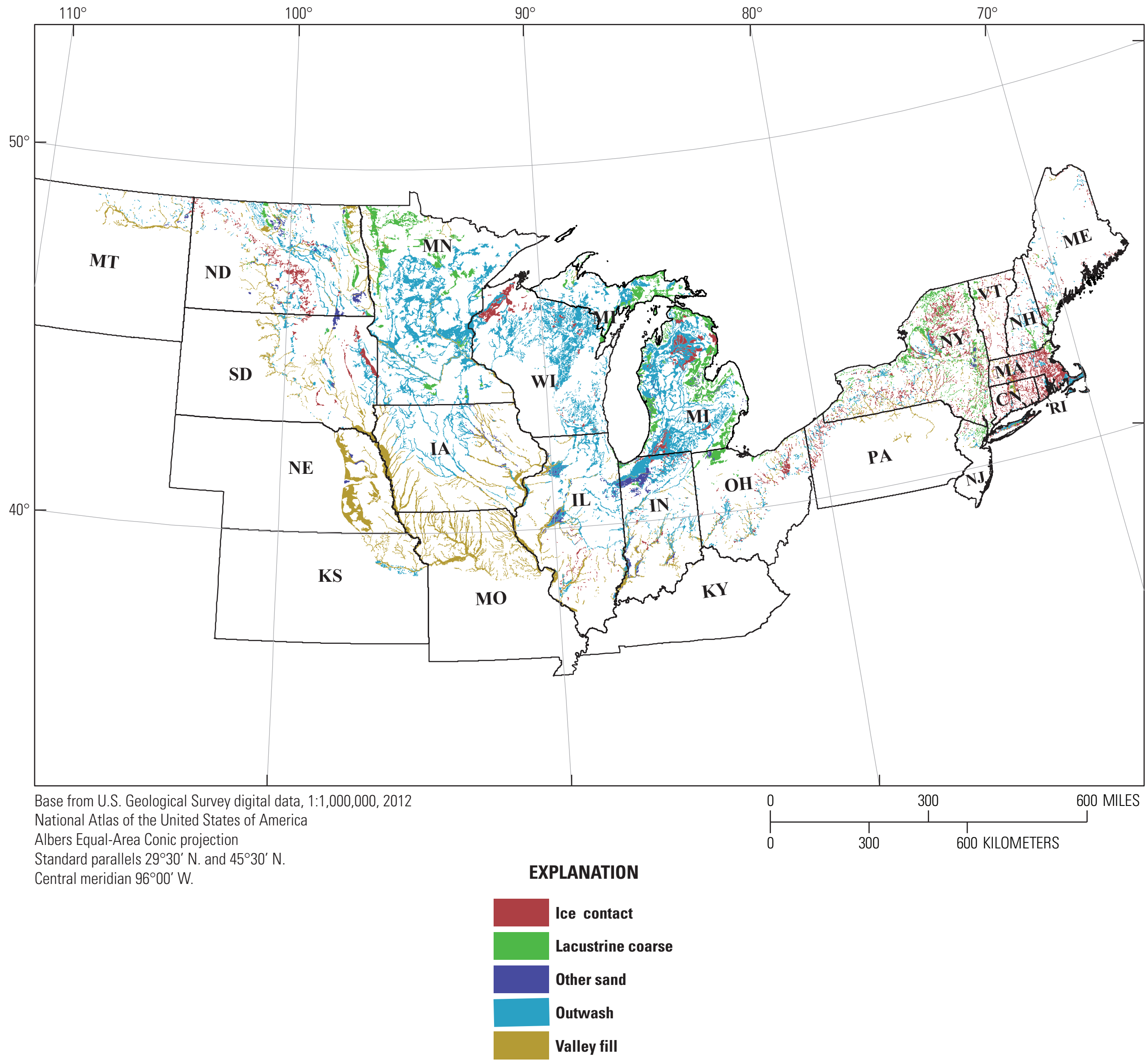


Figure 19. Hydrogeologic framework for the glacial aquifer system study based on classification of mapped units derived from the Quaternary geologic atlas (U.S. Geological Survey and others, 2013) showing classes of aquifer material.

aquifers could include water from surface runoff and exchange with deeper regional systems. These other water sources and sinks are often mediated by fractures in upland tills, bedrock outcrops, and underlying rock units (Kontis and others, 2004). In the Central region, estimates of recharge from Ohio (Dumouchelle and Schiefer, 2002) and Minnesota (Delin and others, 2007), for example, show recharge on areas mapped as till, emphasizing that on a regional scale, these areas may contribute to base flow and could be responsible for part of the recharge to the system. Recharge in the areas mapped as till, however, is less than recharge in the areas mapped as aquifer material consistent with the expected behavior of these settings. This lithologic control on recharge was explored for Nebraska by Gates and others (2014) who found that diffuse recharge in river valleys where till has been removed by erosion was significantly greater than diffuse recharge on areas of upland till and dominated overall recharge to the system. Recharge processes in the coteau du Missouri and similar parts of the West-Central region also occur in till areas and have been attributed to focused recharge in depressions in the till related to wetlands and ponds that can form a regional flow system (van der Kamp and Hayashi, 2009) and potentially deliver water to underlying bedrock aquifers (Long and others, 2014). The appropriate hydrologic framework from

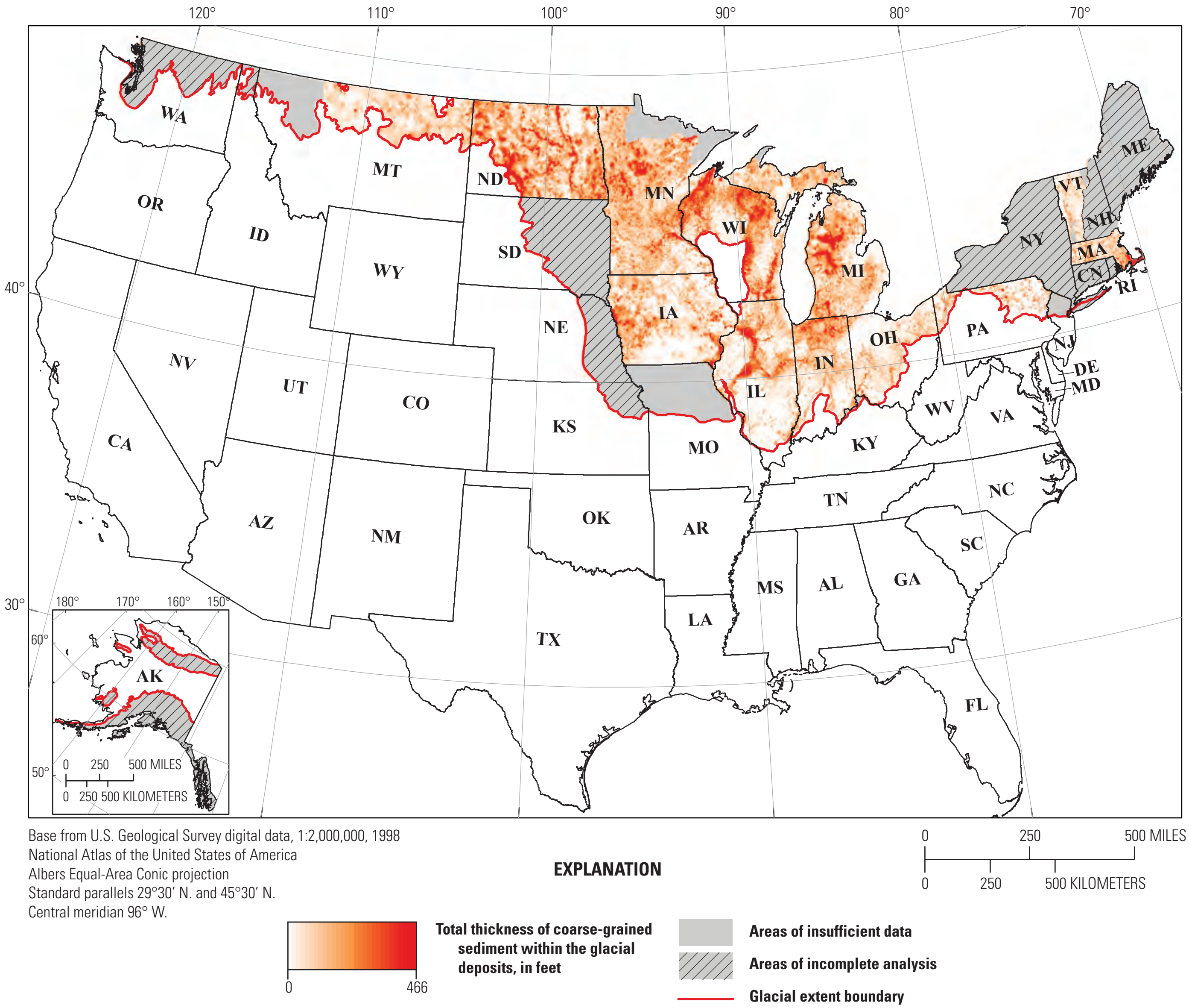


Figure 20. Sand and gravel thickness for the glacial aquifer system derived from analysis of water-well records (from Bayless and others, 2017).

a recharge perspective appears to be a hybrid regional view with regional estimates made by considering net recharge, as indicated by base flow from catchments, combined with classified map units that indicate surficial aquifer material that could have higher recharge potential. If low permeability areas are neglected completely, the resulting recharge estimate for areas mapped as aquifer would be too high when compared to total precipitation or local observations. Note, however, that a mapped unit framework that neglects low-permeability areas can be adopted in the development of a numerical model as long as recharge attributed to bordering nonaquifer units is delivered to the boundary of the numerical model (DeSimone and others, 2002).

Figure 22 provides an estimate of mean annual recharge in inch per year on a 1-km grid for the glacial aquifer system study area except Alaska. Total recharge to the conterminous glacial aquifer system is estimated as 1×10^{13} cubic feet per year or a mean recharge of 6.3 inches per year [in/yr] over the study area. This serves as one estimate for recharge to the glacial aquifer system. The major assumption is that the base

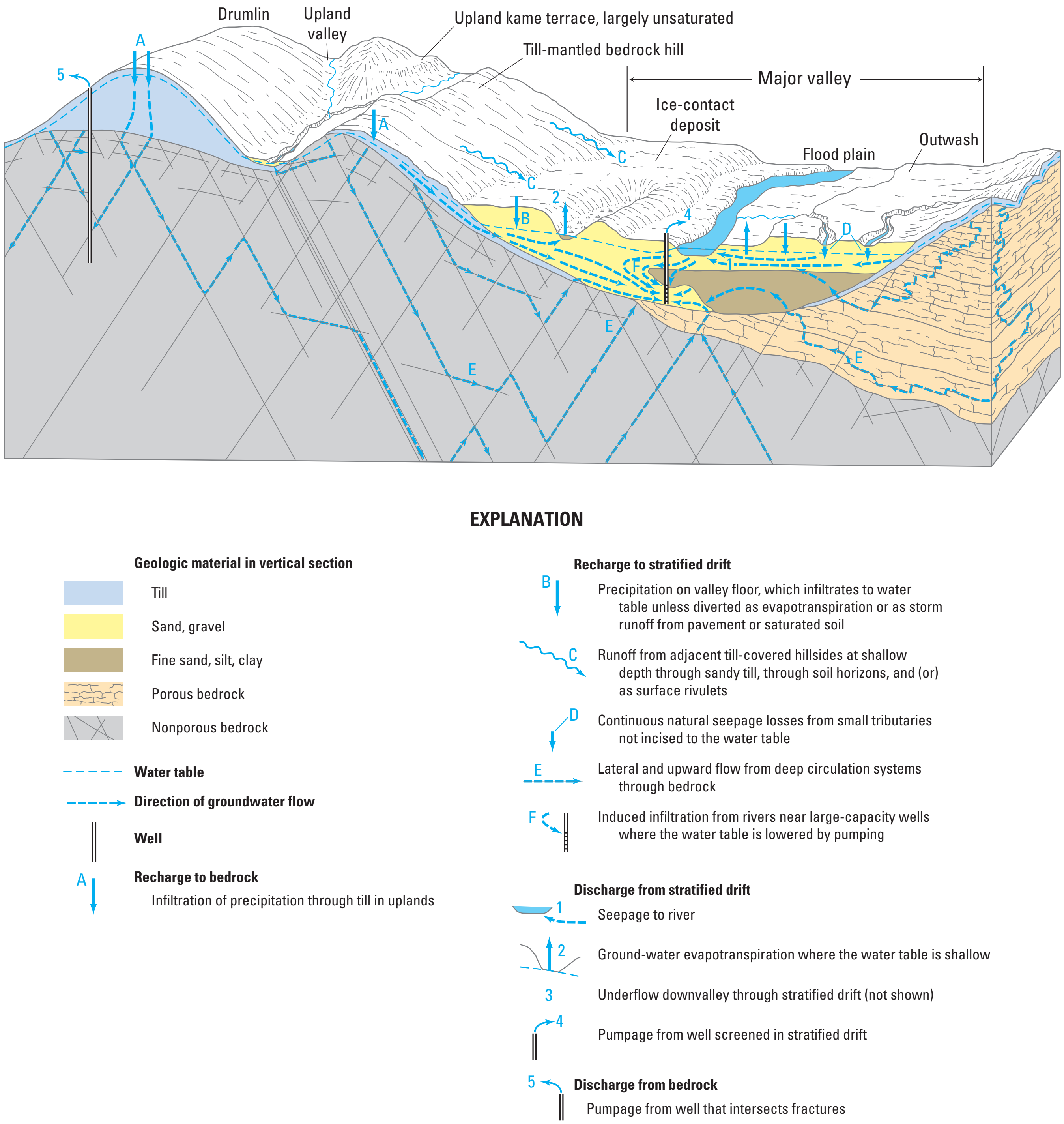


Figure 21. Idealized groundwater-flow paths in a valley-fill aquifer system with till and bedrock uplands showing various recharge mechanisms (from Kontis and others, 2004).

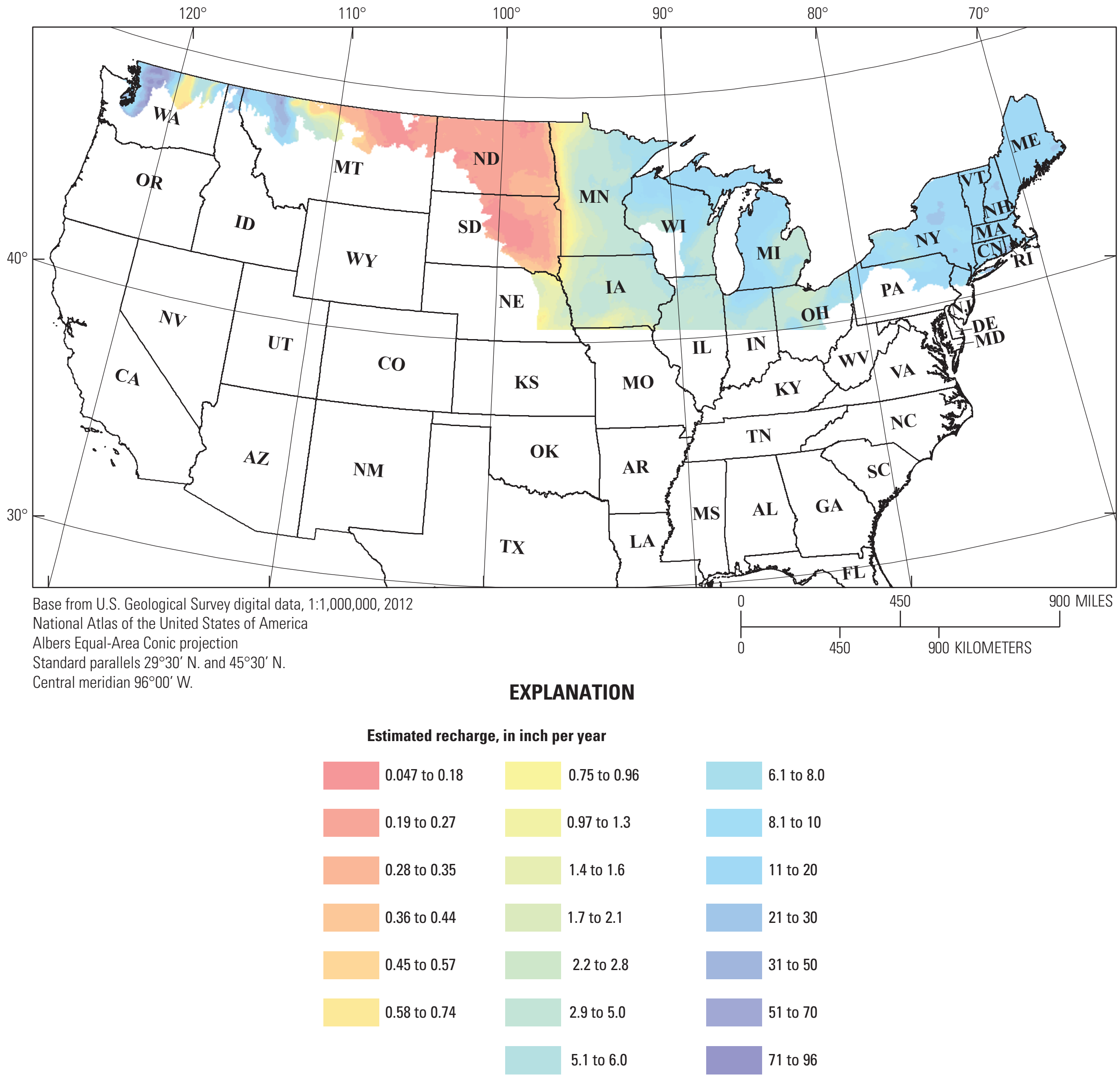


Figure 22. Estimated mean annual recharge for the conterminous glacial aquifer system study area from a grid of the conterminous United States by Wolock (2003b) converted from millimeters per year to inches per year and increased by a factor of 1.2 to align the estimated base-flow index with other base-flow separation methods.

flow at streamgages in the glacial aquifer system study area is dominated by discharge from aquifers, and the amount of recharge to the glacial aquifer system that is exchanged with deeper aquifers either eventually appears as base flow or is small compared to the total recharge. An estimate by Wolock (2003b) based on the BFI method and adjusted by a factor of 1.2 gives a representative value for various base-flow separation methods (figs.7–9).

The estimated recharge grid based on inverse-distance weighting interpolation of estimates of BFI from the GAGES II (Wolock, 2003a) for the East region dataset is smooth and does not recognize patterns in soils or underlying geology in the estimation of recharge (fig. 22). The spatial pattern of recharge, however, has been shown to depend on landscape characteristics such as soils, geology, and topography (Arnold and others, 2000; Delin and others, 2007; Nolan and others, 2007; Santi and others, 2008; Gates and others, 2014), even to the site scale (Fragalà and Parkin, 2010). For the glacial aquifer system, resolution of recharge patterns to the site scale is not feasible; however, application of a soil water balance (SWB) approach (Westenbroek and others, 2009) appears to capture spatial patterns and allows for estimation across most of the study area. Recent work estimating recharge for Minnesota illustrates the performance of SWB (Smith and Westenbroek, 2015), and this type of application across the glacial aquifer system study area could be an important next step. Examining the recharge and discharge estimates by region helps emphasize differences between regions.

East Region

The spatial pattern in the estimated recharge mirrors the spatial distribution of precipitation for the East region (fig. 23). The estimated recharge for this region is 40 percent of the total estimated recharge for the entire glacial aquifer system study area (excluding Alaska), and the average recharge rate is 13 in/yr (total recharge/total area). The estimated range is from 2.8 to 26 in/yr.

Central Region

The spatial pattern in the estimated recharge mirrors the spatial distribution of precipitation for the Central region (fig. 24). The estimated recharge for this region is 32 percent of the total estimated recharge for the entire glacial aquifer system study area (excluding Alaska), and the average recharge rate is 6.3 in/yr. The estimated range is from less than 1 to 17 in/yr.

West-Central Region

The spatial pattern in the estimated recharge mirrors the spatial distribution of precipitation for the West-Central region (fig. 25). Despite its large area, the estimated recharge for this region is only 11 percent of the total estimated recharge for the entire glacial aquifer system study area (excluding Alaska), and the average recharge rate is 1.6 in/yr. The estimated range is from less than 1 to 33 in/yr.

West Region

The spatial pattern in the estimated recharge mirrors the spatial distribution of precipitation for the West region excluding Alaska (fig. 26). Alaska is not included in the estimates because the data sources do not include Alaska. The estimated recharge for this region is the remaining 17 percent of the total estimated recharge for the entire glacial aquifer system study area (excluding Alaska), and the average recharge rate is 20 in/yr. The estimated range is from less than 1 to 96 in/yr. Note that the bibliography report published by Kahle and Futornick (2012) denotes reports with recharge estimates in the West region with a ”B” in the “Information Code” for the report.

Water Withdrawals

Groundwater withdrawals from the glacial aquifer system in 2000 were 5 percent of the total reported groundwater withdrawals (Maupin and Barber, 2005), and the study disaggregating groundwater withdrawals for the calendar year 2000 national compilation by principal aquifer (Maupin and Barber, 2005) may be used to estimate water withdrawals from the glacial aquifer system for 2005 and 2010. Estimated withdrawals from the glacial aquifer system across the study area are greatest in the Central region. The withdrawals from the Central region are estimated to be 2–3 times larger than either the West-Central or East regions, and the West region has the lowest estimated withdrawal (fig. 27). Public supply withdrawals are the largest withdrawals in the Central and East. The largest withdrawals in the West are for public supply or aquaculture depending on the year. Irrigation withdrawals are the largest in the West-Central region and important in the Central region (fig. 28). Public supply withdrawals declined slightly from 2000 to 2010, which is consistent with the national trends (Maupin and others, 2014). Compared to other principal aquifers, the glacial aquifer system provides the most public supply and self-supplied industrial withdrawals (Maupin and Barber, 2005).

Storage and Changes in Storage

Groundwater storage can mitigate the effects of seasonal changes in rainfall or droughts that would affect riverine or surface-water water-supply reservoirs by providing a stable source of water for various uses. The glacial aquifer system study area is very large, and the resulting total storage, even for each of the four regions, is so large that total storage in the area does not inform groundwater availability. Local storage properties and the hydraulics associated with accessing this storage influence groundwater availability (Alley, 2007). Storage is also estimated in other regional studies, and, for

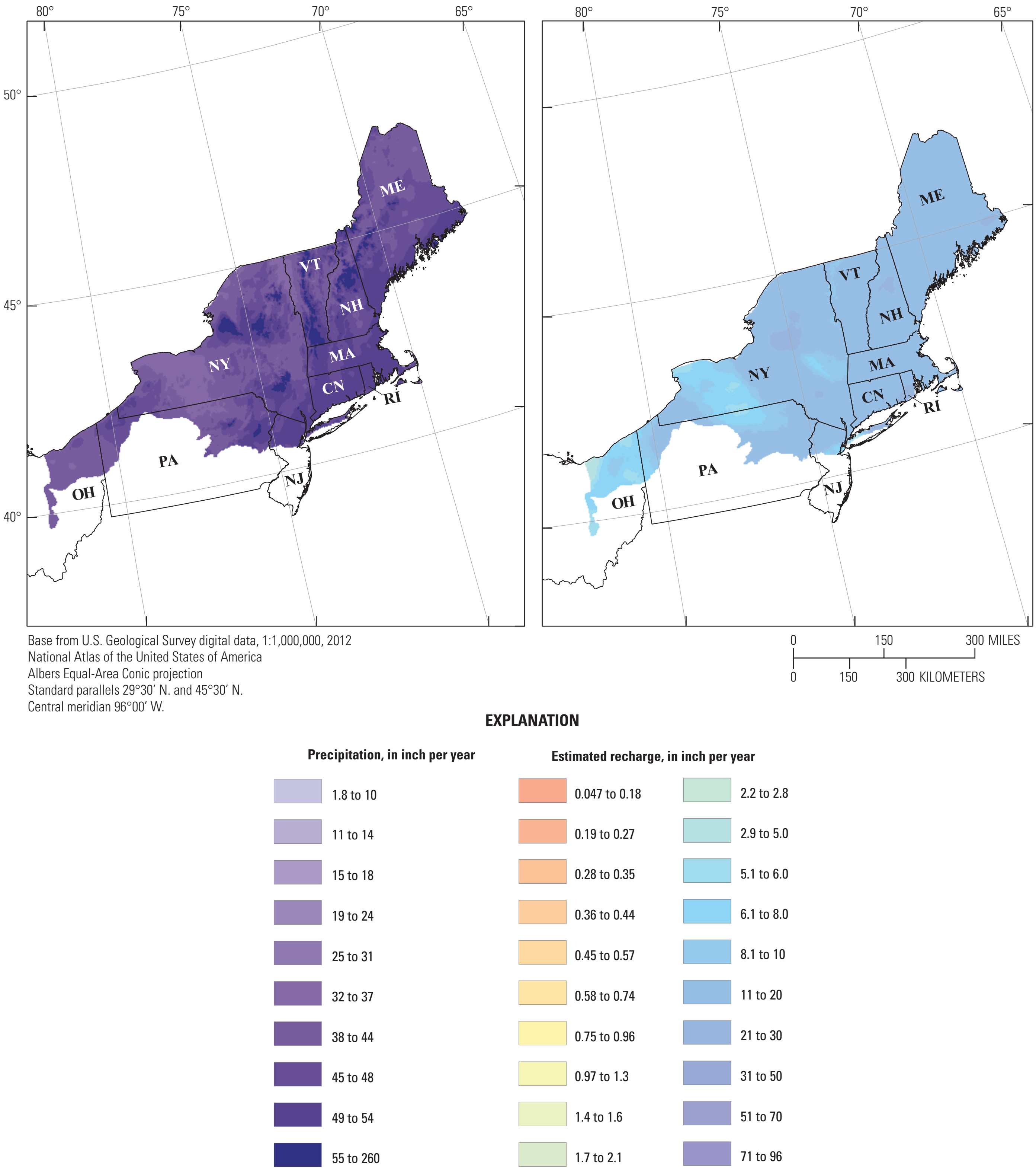


Figure 23. Estimated mean annual precipitation for the period 1981–2010 (PRISM Climate Group; Oregon State University, 2004; Daly and others, 2008) and estimated recharge (from Wolock, 2003a) for the East region of the study area.

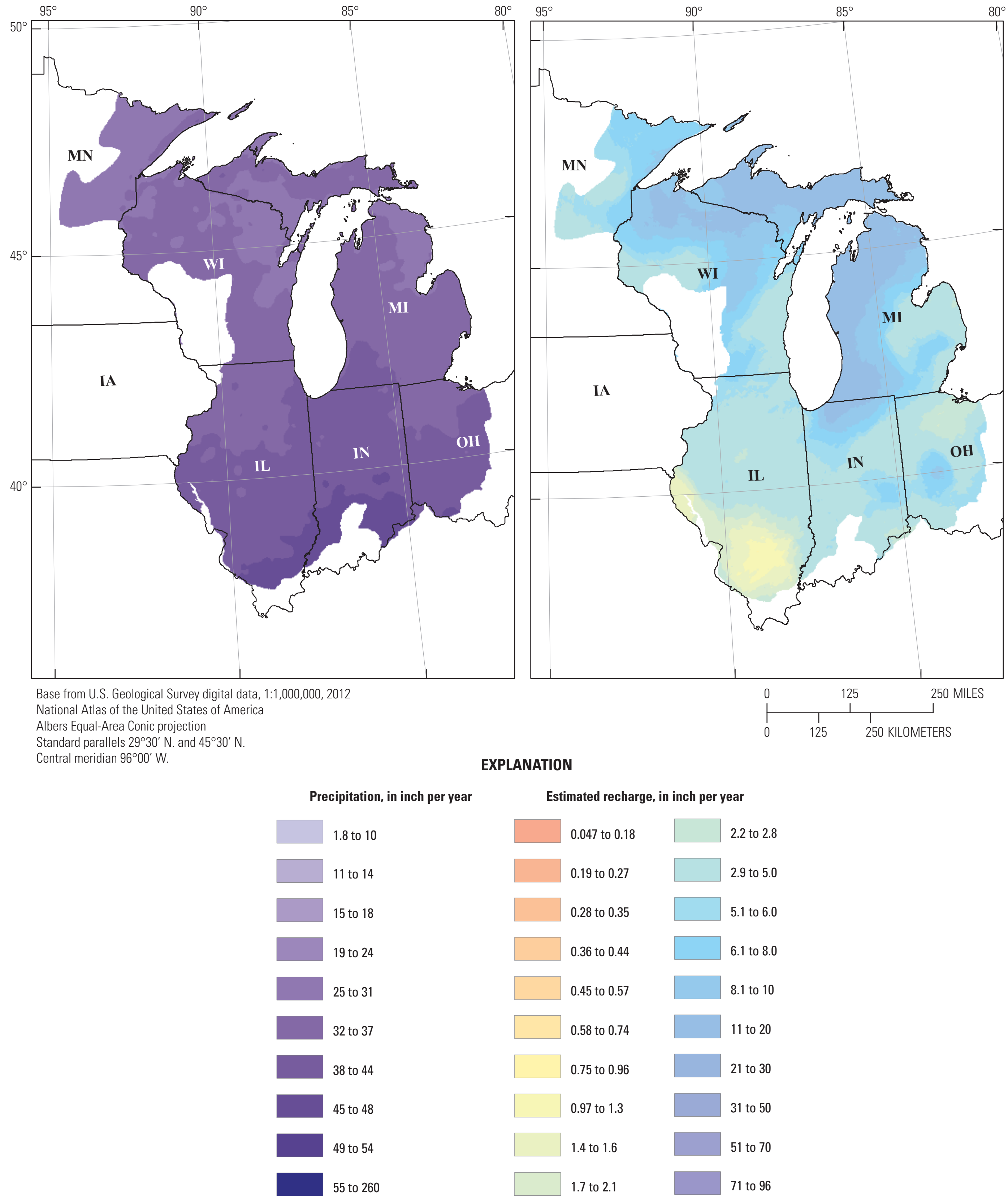


Figure 24. Estimated mean annual precipitation for 1981–2010 (PRISM Climate Group; Oregon State University, 2004; Daly and others, 2008) and estimated recharge (from Wolock, 2003a) for the Central region of the study area.

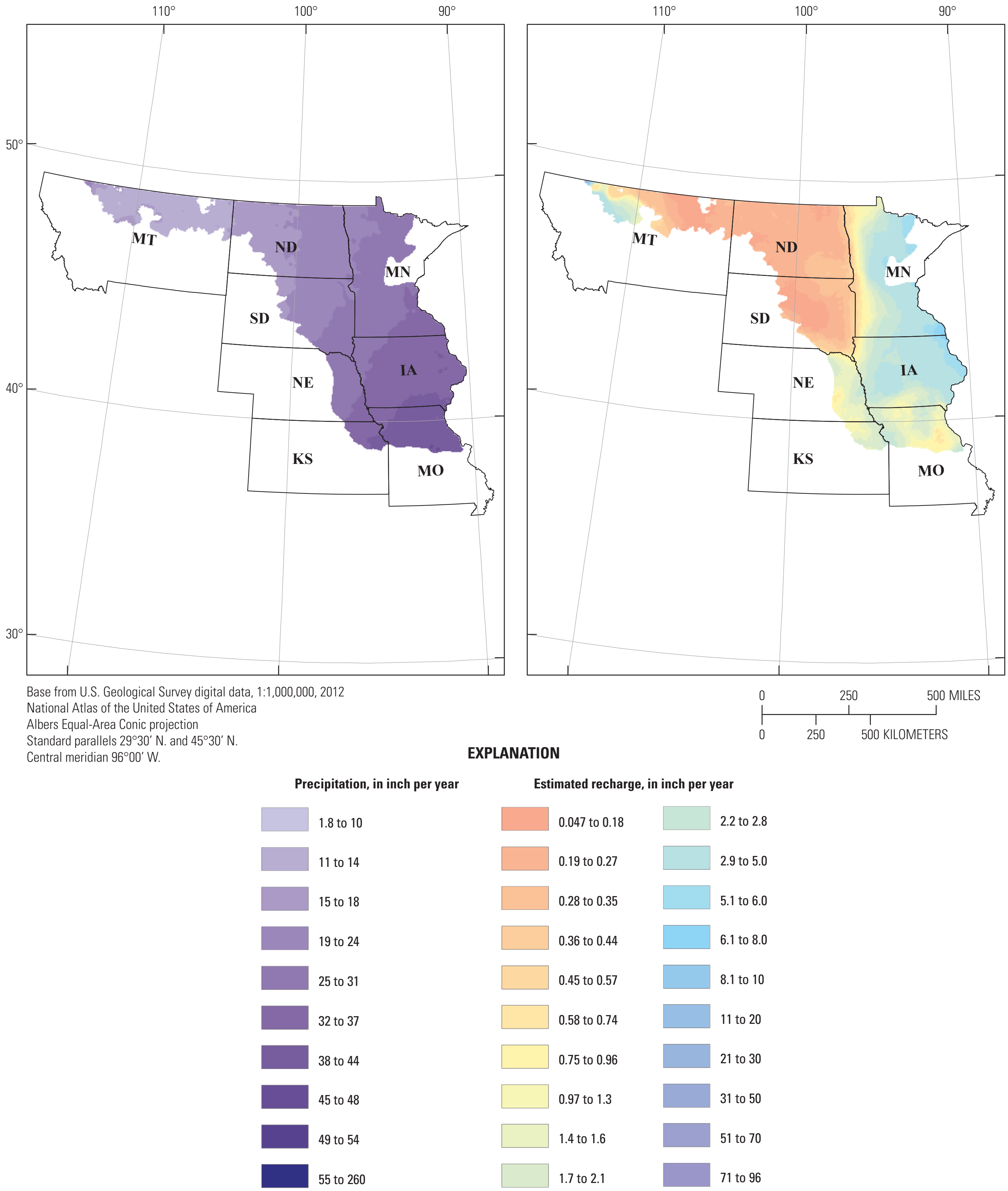


Figure 25. Estimated mean annual precipitation for 1981–2010 (PRISM Climate Group; Oregon State University, 2004; Daly and others, 2008) and estimated recharge (from Wolock, 2003a) for the West-Central region of the study area.

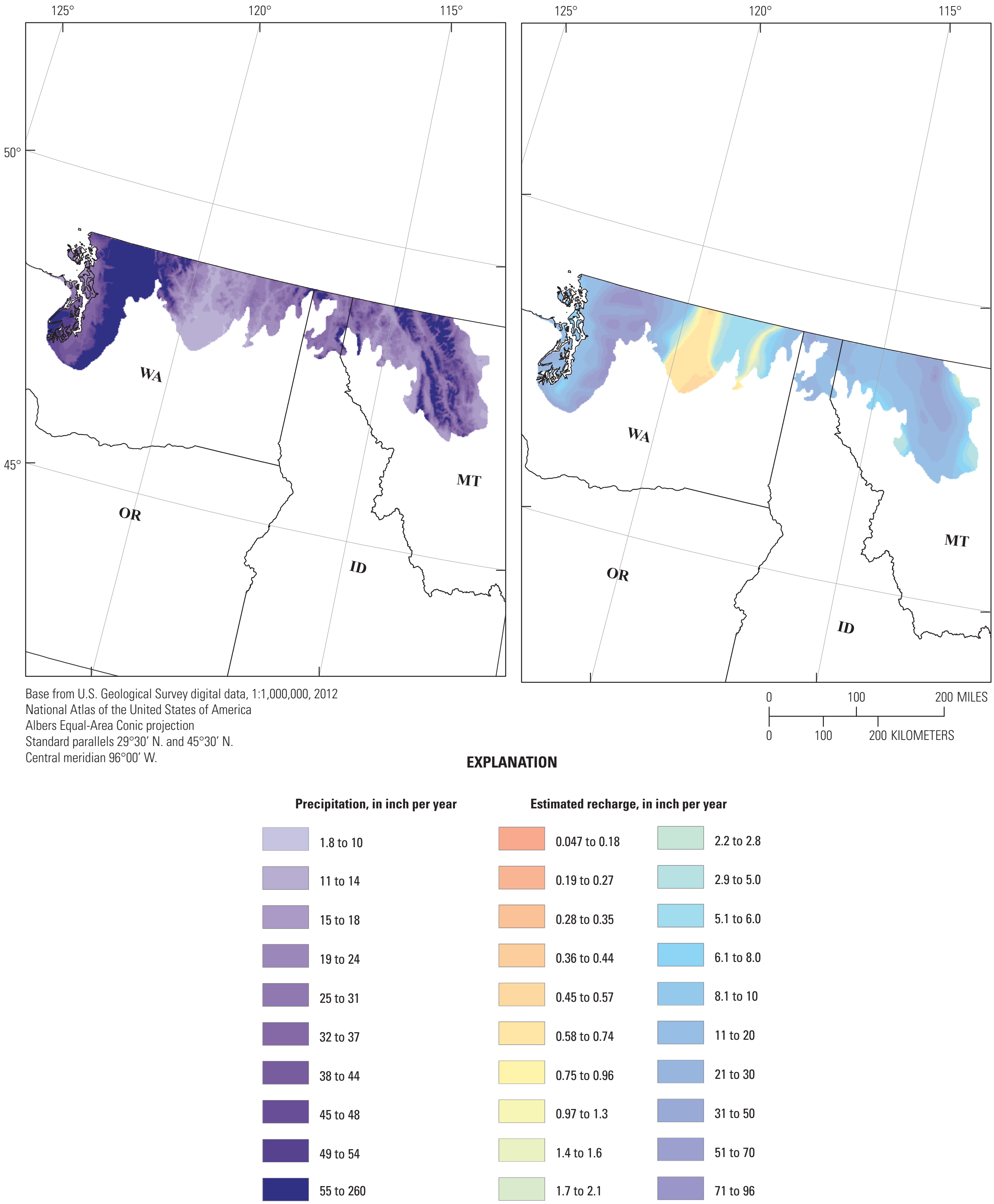


Figure 26. Estimated mean annual precipitation for 1981–2010 (PRISM Climate Group; Oregon State University, 2004; Daly and others, 2008) and estimated recharge (from Wolock, 2003a), for the West region of the study area although neither data source includes estimates for Alaska.

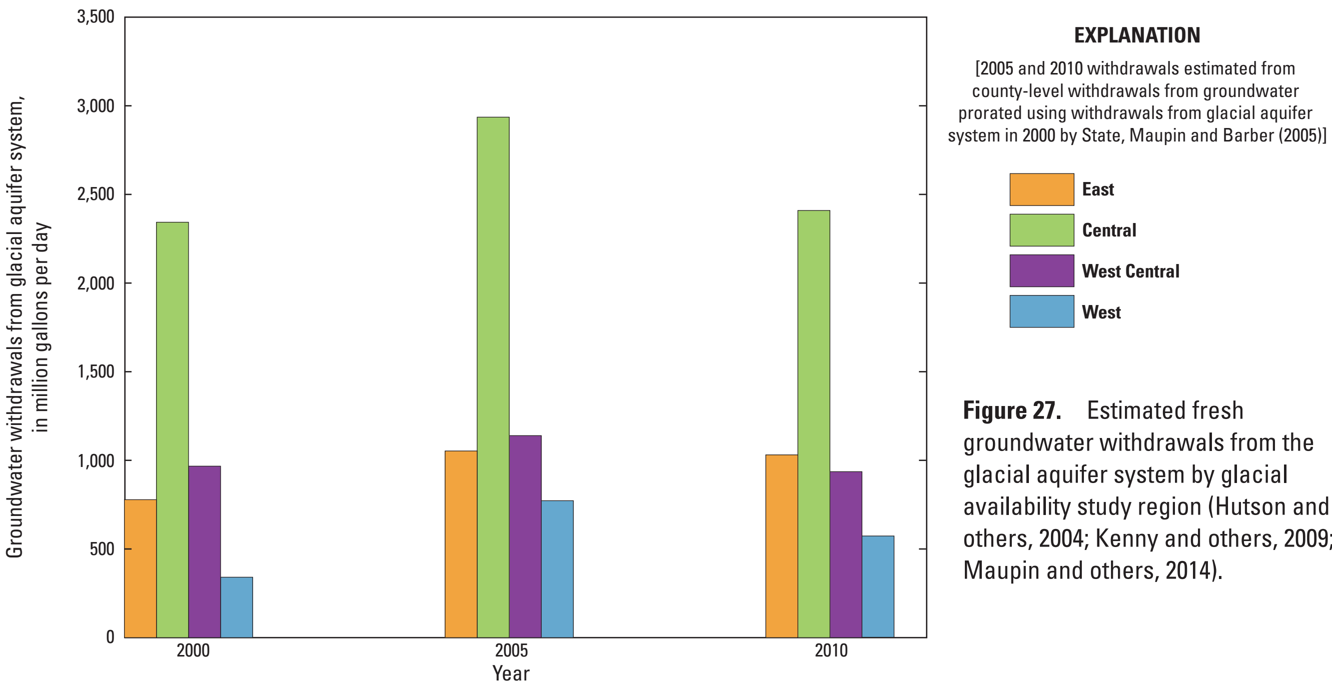


Figure 27. Estimated fresh groundwater withdrawals from the glacial aquifer system by glacial availability study region (Hutson and others, 2004; Kenny and others, 2009; Maupin and others, 2014).

purposes of comparison, simple estimates of total storage are presented.

Following the procedure of Coon and Sheets (2006), accounting for aquifer storage including both specific yield (storage release by drainage of the pore space in the aquifer material) and specific storage (storage release by the expansion of water and compression of the aquifer matrix) (eq. 1), requires estimates of aquifer material storage characteristics. As discussed, the base map by Soller and others (2011) was used in this estimate. Representative values from Coon and Sheets (2006) were used for S_y and S_s in equation 1, and the fraction of the area covered by aquifer material was estimated from attributes of the mapped units. For the current estimate, similar values of S_y and S_s were assigned to the mapped surficial units designated as coarse stratified (Soller and others, 2011). The specific yield for the thickest units was set to zero following the assumption used by Coon and Sheets (2006) that storage for units with a thickness greater than 400 ft was primarily from confined materials (table 6).

For the initial estimation of storage, selection of only areas of coarse-stratified sediments of the glacial aquifer system was done to be consistent with the approach used by Coon and Sheets (2006). The groundwater storage was estimated using the values in table 6 and equation 1, and the total storage is 630 mi^3. This value is approximately 8 percent greater than the estimate from Coon and Sheets (2006), which was considered satisfactory for this analysis.

Application of this method to regions of the glacial aquifer system yields estimates of storage for the East, Central, and West-Central glacial aquifer study regions (table 7). Storage was not estimated for the West region because few groundwater-level data were available and the glacial deposits in this region are often discontinuous. Because some water use, particularly self-supplied domestic, may access parts of the aquifer mapped as fine-grained stratified or even till, a second estimate was made including these materials. For this estimate, the specific yield of the units was set quite low, 0.01, assuming that water does not drain from these materials very well (table 6). This estimate is the difference between the aquifer material storage value and the total glacial aquifer system storage value in table 7.

Comparison of the aquifer material storage to annual water use indicates that total groundwater withdrawals are less than 1 percent and as low as 0.2 percent of the volume of groundwater in storage. As discussed by Coon and Sheets (2006), these estimates are general, and they serve primarily as a comparison to other systems. Importantly, groundwater mining, or continued loss in storage in response to pumping, is not observed across the study area (Bartolino and Cunningham, 2003; Konikow, 2013, 2015). Local storage loss and its effect on well owners or base flow can be important in parts of the study area (Alley, 2007; Kraft and others, 2012), but widespread loss is not documented.

Some principal aquifer systems are experiencing groundwater mining, or substantial declines in groundwater levels defined as losses in tens to hundreds of feet (Bartolino and Cunningham, 2003); these declines generally are not observed for the glacial aquifer system despite locally large withdrawals for various uses. There are three reasons why the glacial aquifer system has not experienced such dramatic changes in water levels:

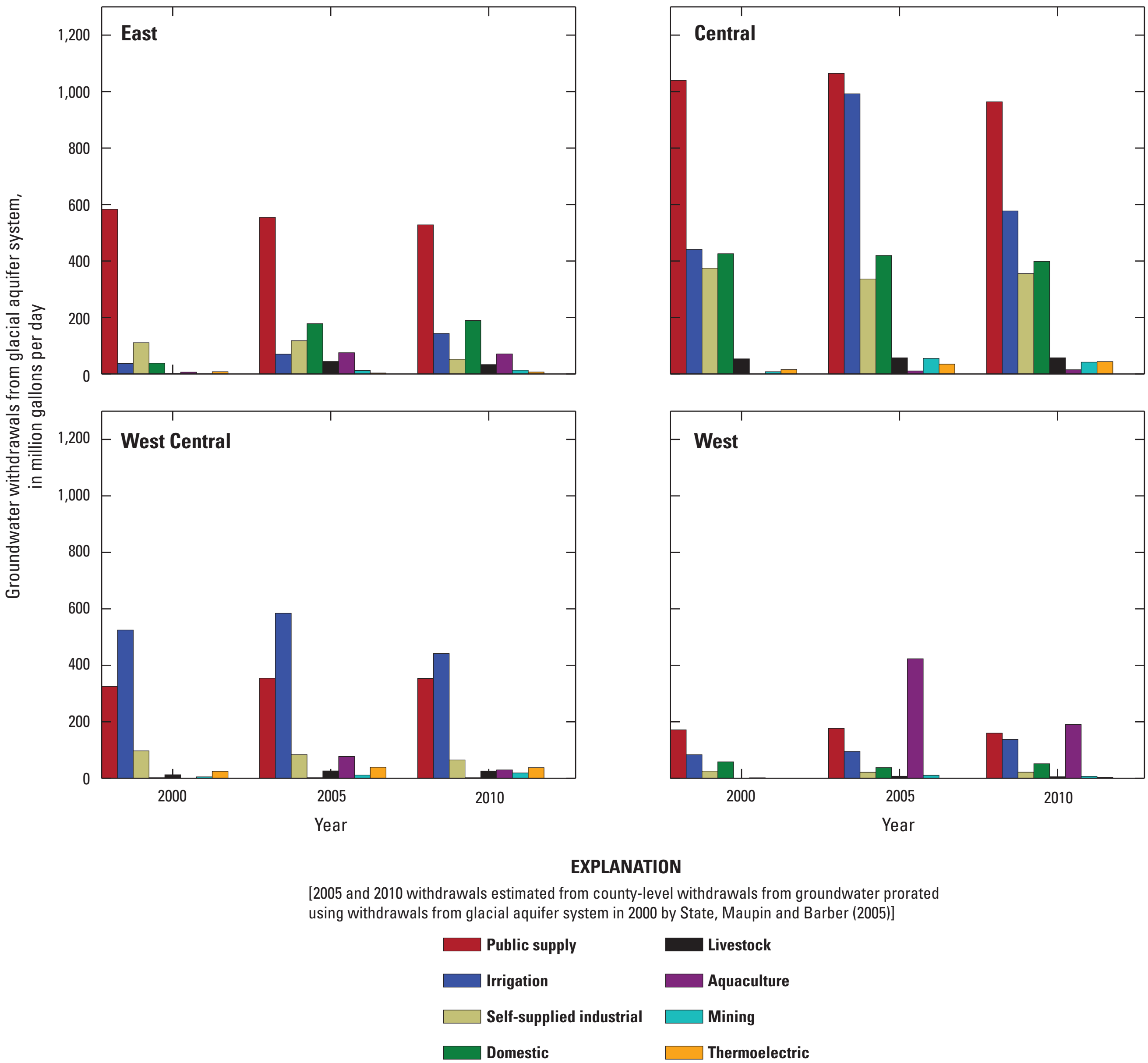


Figure 28. Estimated fresh groundwater withdrawals from the glacial aquifer system by type and glacial availability study region (Hutson and others, 2004; Kenny and others, 2009; Maupin and others, 2014).

Table 6. Mapped unit (Soller and other, 2011) and representative thickness and specific yield and specific storage values assigned for estimation of groundwater in storage.

[ft^{-1}, 1/foot; ft, foot]

Unit	Representative saturated thickness, in ft	Specific yield, dimensionless	Specific storage, ft^{-1}
Coarse-grained stratified sediment, Quaternary sediment 0–50 ft thick	30	0.13	0.00080
Coarse-grained stratified sediment, Quaternary sediment 100–200 ft thick	160	0.13	0.00080
Coarse-grained stratified sediment, Quaternary sediment 1,000–1,200 ft thick	1,150	0.13	0.00080
Coarse-grained stratified sediment, Quaternary sediment 200–400 ft thick	330	0.13	0.00080
Coarse-grained stratified sediment, Quaternary sediment 400–600 ft thick	525	0.00	0.00080
Coarse-grained stratified sediment, Quaternary sediment 50–100 ft thick	80	0.13	0.00080
Coarse-grained stratified sediment, Quaternary sediment 600–800 ft thick	720	0.00	0.00080
Coarse-grained stratified sediment, Quaternary sediment 800–1,000 ft thick	950	0.00	0.00080
Exposed bedrock, or sediment not of glacial origin 0–50 ft thick	0	0.00	0.00000
Values assigned to fine-grained material for second estimate of total storage, specific yield and specific storage set to zero in initial estimate			
Fine-grained stratified sediment, Quaternary sediment 0–50 ft thick	30	0.01	0.00060
Fine-grained stratified sediment, Quaternary sediment 100–200 ft thick	160	0.01	0.00060
Fine-grained stratified sediment, Quaternary sediment 1,000–1,200 ft thick	1,150	0.01	0.00060
Fine-grained stratified sediment, Quaternary sediment 1,200–1,400 ft thick	1,350	0.01	0.00060
Fine-grained stratified sediment, Quaternary sediment 1,400–1,600 ft thick	1,550	0.01	0.00060
Fine-grained stratified sediment, Quaternary sediment 200–400 ft thick	330	0.01	0.00060
Fine-grained stratified sediment, Quaternary sediment 400–600 ft thick	525	0.01	0.00060
Fine-grained stratified sediment, Quaternary sediment 50–100 ft thick	80	0.01	0.00060
Fine-grained stratified sediment, Quaternary sediment 600–800 ft thick	720	0.01	0.00060
Fine-grained stratified sediment, Quaternary sediment 800–1,000 ft thick	950	0.01	0.00060
Fine-grained stratified sediment, Quaternary sediment more than 1,600 ft thick	1,600	0.01	0.00060
Organic-rich sediment, 0–50 ft thick	30	0.01	0.00010
Patchy Quaternary sediment, 0–50 ft thick	25	0.10	0.00010
Till, Quaternary sediment 0–50 ft thick	30	0.01	0.00010
Till, Quaternary sediment 100–200 ft thick	160	0.01	0.00010
Till, Quaternary sediment 1,000–1,200 ft thick	1,150	0.01	0.00010
Till, Quaternary sediment 1,200–1,400 ft thick	1,350	0.01	0.00010
Till, Quaternary sediment 200–400 ft thick	330	0.01	0.00010
Till, Quaternary sediment 400–600 ft thick	525	0.01	0.00010
Till, Quaternary sediment 50–100 ft thick	80	0.01	0.00010
Till, Quaternary sediment 600–800 ft thick	720	0.01	0.00010
Till, Quaternary sediment 800–1,000 ft thick	950	0.01	0.00010

Table 7. Estimated groundwater storage in the glacial aquifer system.

[--, storage for West region was not estimated]

Region	Aquifer material storage, in cubic miles	Fine-grained material storage, in cubic miles	Total glacial aquifer system storage, in cubic miles
East	67	30	97
Central	800	160	960
West-Central	610	370	980
West	--	--	--

1. As the shallowest available aquifer generally composed of unconsolidated sediment, the glacial aquifer system acts as an unconfined aquifer in most parts of the study area. Under unconfined conditions, storage release from the aquifer material is a result of the drainage of the pore space that is characterized by the aquifer specific yield (Freeze and Cherry, 1979). Specific yield may be on the order of 0.1 in contrast to the confined storativity (specific storage × thickness) of an aquifer that may be on the order of 0.001–0.0001; therefore, a water-level change of 1 ft in an unconfined aquifer is equivalent to a change of 100 ft in a confined aquifer.

2. To observe very large drawdowns in water levels, an aquifer must be subjected to pumping and have hydraulic characteristics that lead to storage loss rather than capture of water from discharge or other boundaries (Bredehoeft, 2002). For example, observed changes in the Cambrian-Ordovician system in northwestern Illinois and southeastern Wisconsin require a fairly unique set of circumstances: deep aquifers of sufficient quality for desired use, large initial head, low specific storage, and moderate transmissivity. For the bedrock aquifers below Chicago, the initial static head in a bedrock aquifer at a depth of 710 ft was as much as 80 ft above land surface in the 1860s (Schufeldt, 1866) and had experienced nearly 230 ft of drawdown from development by 1910 (Anderson, 1919). Deeper wells and continued use led to drawdowns on the order of 900 ft by the mid-1960s (Mandle and Kontis, 1992). There are no examples of confined parts of the glacial aquifer system with geometry and hydraulic characteristics that could give this type of behavior.

3. Finally, because the glacial aquifer system can be shallow and hydraulically well connected to surface water, pumping in some parts of the glacial aquifer system quickly is balanced by either capture of water that would have discharged to surface water or capture of induced recharge from surface water (Barlow and Leake, 2012). Streamflow capture also is noted for confined aquifer systems; therefore, confinement of glacial sediments does not preclude streamflow capture limiting water-level declines, rather confinement of the system may slow the time required to reach a steady state with no further declines (Leake, 2011; Barlow and Leake, 2012).

Despite not having dramatic changes in water levels in the aquifer system, significant loss of water from storage in the glacial aquifer system has been noted (Konikow, 2013). Some of the distributed storage loss in the glacial aquifer system is associated with drainage tiles that were installed in the mid-1800s to allow for transportation and agriculture in many parts of the study area (Kaatz, 1955; Dahl and Allord, 1999). Konikow (2013) estimates that land drainage in the conterminous United States has led to a storage loss of 13 mi^3. This drainage was critical for successful agriculture and westward expansion, and much of the drained land is within the study area; however, the effect on groundwater availability is likely minimal. Soils requiring tile drainage naturally dominate in areas that do not serve as productive surficial aquifers, and the local decline in groundwater level in these areas is on the order of 3–5 ft.

Storage change is observed in groundwater levels in monitoring wells. These observations may be augmented by the GRACE satellite system that provides remote-sensed data that may be useful in quantifying storage change (Chen and others, 2005). The GRACE data have been used to quantify water loss in the Central Valley of California (Famiglietti and others, 2011), the Amazon River (Chen and others, 2009), and other large systems, including the Great Lakes (Huang and others, 2012). The Great Lakes study in particular discusses the difficulty of detecting changes in groundwater storage using GRACE in a large humid system. The GRACE data indicate changes in the gravity field of the earth from several mechanisms, including changes in total water storage: surface water, soil moisture, snow, ice, and groundwater (Huang and others, 2012). The use of GRACE data to quantify changes in groundwater storage requires that the change in total water storage data be analyzed and distributed between these potential water sources.

Data from the GRACE satellite system were analyzed to estimate changes in total water storage using published methods (Swenson and Wahr, 2006; Landerer and Swenson, 2012), and the results for the four glacial aquifer system regions are shown in figure 29. The analysis confirmed the earlier discussion by Huang and others (2012) that the change in total terrestrial water storage is difficult to relate to changes in groundwater in storage. The GRACE satellite data are a significant independent data source that may be used to constrain or interpret regional (Zaitchik and others, 2008) or global (Döll and others, 2014) water-resources models, but these data require significant direct observations of groundwater level, soil moisture, surface-water storage, snowpack, and likely hydrologic models to resolve the various components of water storage.

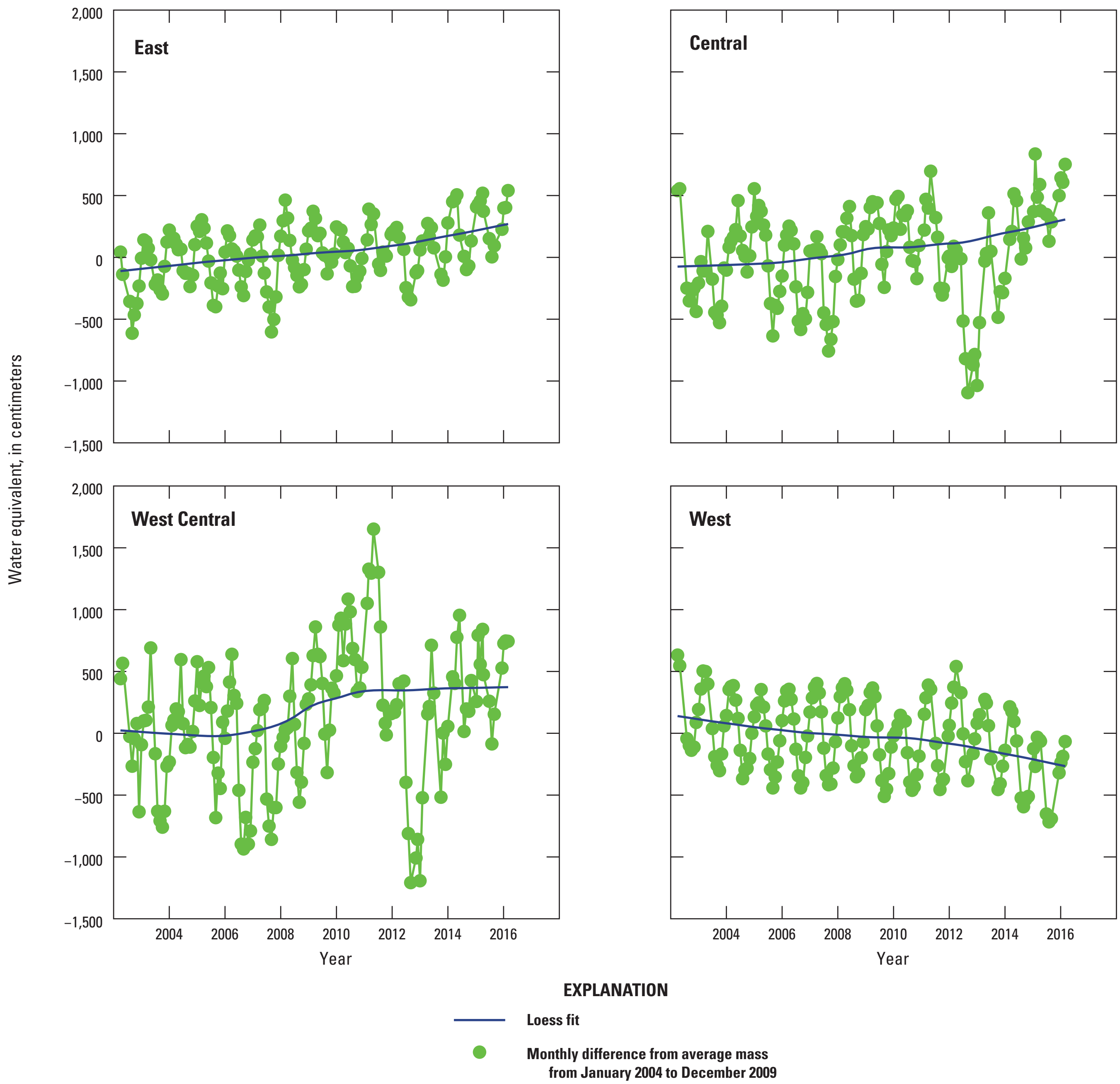


Figure 29 Changes in terrestrial water storage derived from GRACE satellite data from 2002 to 2014. GRACE land data available at https://grace.jpl.nasa.gov, supported by NASA MEaSUREs Program (Landerer and Swenson, 2012; Swenson, 2012; Swenson and Wahr, 2006).

Groundwater Budgets

Generalized groundwater budgets for each of the four regions in the glacial aquifer system were developed from (1) the long-term annual recharge and discharge based on Wolock (2003b) as increased to be representative of various base-flow separation estimates; (2) averaged withdrawals from the glacial aquifer system for 2000, 2005, and 2010 estimated by applying the ratio of groundwater withdrawals from the glacial principal aquifer for 2000 to total groundwater withdrawals reported for 2000, 2005, and 2010; and (3) storage estimated using representative thickness, specific yield, and specific storativity values. Recharge estimates vary for the four regions because of differences in climate and the area of each region. The low recharge rate in the West-Central region is offset by the large area of this region in the estimate of the annual volume of recharge; conversely, high recharge rates in the East region do not produce as large of an annual volume of recharge because this region has the smallest area.

Water withdrawals in most of the four regions are orders of magnitude smaller than other discharges; therefore, estimated discharges and recharge are set equal (fig. 30, table 8). Pumping from the glacial aquifer system and underlying bedrock aquifers will change the local groundwater flow dynamics. Pumping can capture groundwater that would have been discharged to surface water or directly lost to evapotranspiration, changes in groundwater levels in the glacial aquifer system, or adjacent aquifers will change the rate of exchange of water between the systems. Groundwater-flow models are required to estimate the response of the system to pumping. For example, in the Central region, pumping in the Lake Michigan Basin changes the exchange of water between shallow and deep systems and decreases the discharge of groundwater to surface water (Feinstein and others, 2010). In the East region, changes in withdrawals also are anticipated to be balanced by capturing water that would have discharged to streams or inducing leakage from streams to the aquifer system. DeSimone and others (2002) presented detailed analysis for potential changes in base flow to stream reaches in response to changes in pumping or recharge.

Table 8. Summary of generalized annual water budgets for four regions of glacial aquifer system study.

[--, storage for West region was not estimated]

	East	Central	West Central	West
Storage, in cubic miles	97	960	980	--
Recharge rate, in inches per year	13	6.3	1.6	20
Annual recharge, in cubic miles	28.3	22.2	7.5	12.2
Annual discharge, in cubic miles	28.3	22.2	7.5	12.2
Annual withdrawals, in million gallons per day (average of 2000, 2005, and 2010 estimates)	4.6	12	1,010	562
Annual withdrawals, in cubic miles (average of 2000, 2005, and 2010 estimates)	0.32	0.85	0.33	0.19

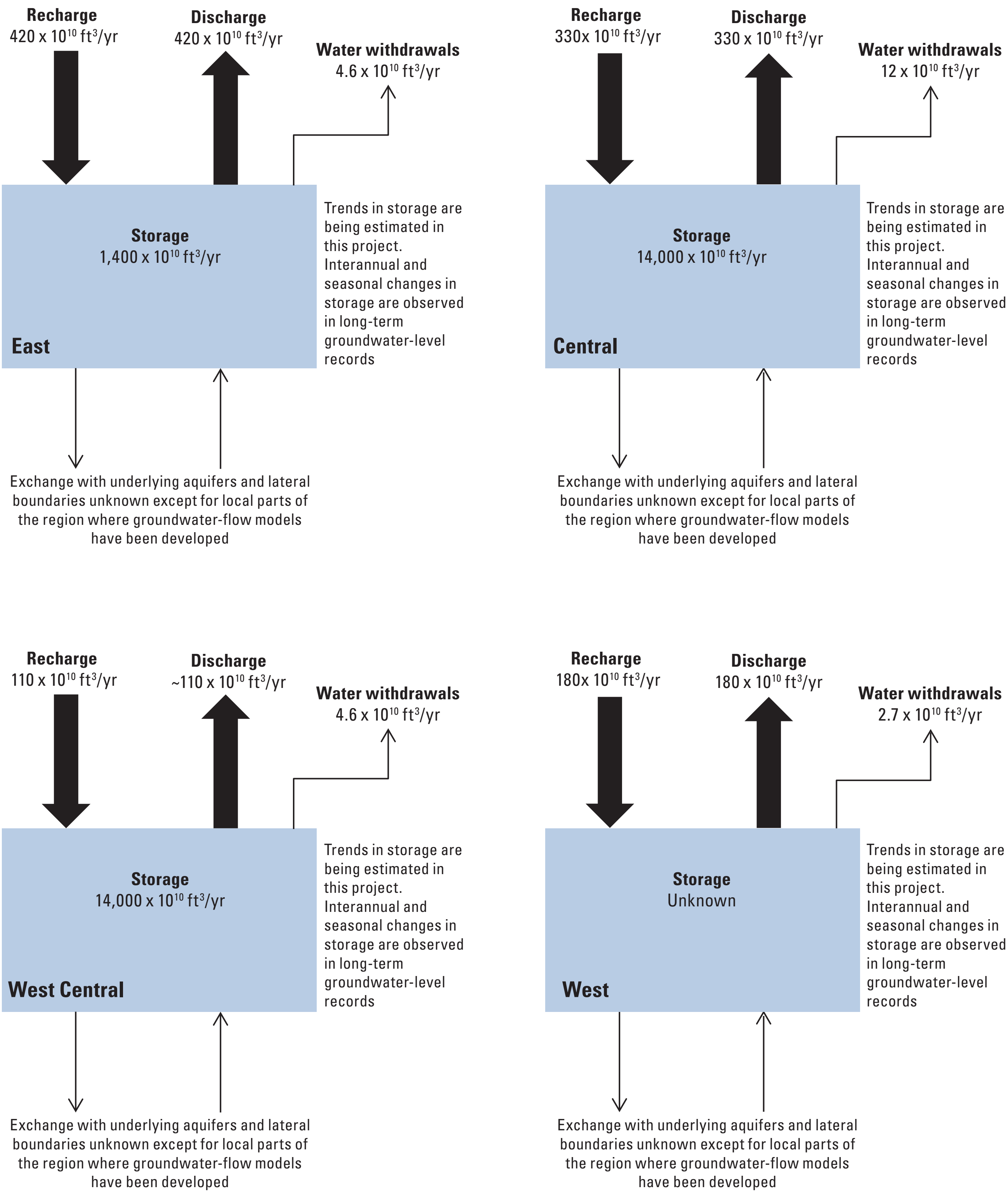


Figure 30. Estimated storage, recharge, discharge, and groundwater withdrawals (in cubic foot per year [ft^3/yr]) for the four glacial aquifer system regions. Note that total withdrawals are small compared to recharge and discharge and were not considered to change the significant figures of the estimated values.

Summary

Water availability in the glacial aquifer system in the United States is quantified by (1) understanding the status of groundwater resources in the glacial aquifer system, (2) determining how these resources have changed over time, and (3) assessing likely system response to future changes in anthropogenic and environmental conditions.

These three goals are common to related regional groundwater availability studies and serve as a basis of a national assessment of groundwater resources. The glacial aquifer system extends from Maine to Alaska, although the focus of this report is the part of the system in the conterminous United States east of the Rocky Mountains. The glacial aquifer system is the largest source for public and self-supplied industrial supply for any principal aquifer, and the system is also an important source for irrigation supply. Despite its importance for water supply, water levels in the glacial aquifer system are generally stable varying with climate and only locally from pumping.

The need for information regarding the distribution of glacial deposits with depth was identified in the development of the hydrogeologic framework for the study. Many of the States in the study area have water-well records in digital databases, and the effort to assemble and interpret these data will be most useful for regional analyses. The hydrogeologic framework for this project includes the information from water-well records and classification of material types from the U.S. Geological Survey Quaternary geologic atlas into likely aquifers dominated by sand and gravel deposits.

Generalized groundwater budgets across the study area highlight the variation in recharge and discharge primarily driven by climate. Future efforts could focus on quantifying spatial and temporal patterns of recharge to provide water managers with more information on observed changes in the system.

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