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# Effects of Climate Variability and Change on Groundwater Resources of the United States

## Abstract

Groundwater is an important part of the global freshwater supply and is affected by climate. U.S. Geological Survey (USGS) scientists are working with local, State, Federal, and international partners to understand how the availability and sustainability of groundwater resources in the United States will be affected by climate variability and change. This fact sheet describes climate variability and change, important groundwater resources of the Nation, and how USGS research is helping to answer critical questions about the effects of climate on groundwater.

## Climate Variability and Change

Climate influences all life on Earth, human health and well-being, water and energy resources, agriculture, forests and natural landscapes, air quality, and sea levels (U.S. Geological Survey, 2007a). The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report of 2007 summarizes evidence that human activities have resulted in climate change. In addition to increases in global average air and ocean temperatures, many scientific studies indicate widespread melting of snow and ice; rising sea levels; widespread changes in precipitation amounts, ocean salinity, and wind patterns; and increasing occurrences of extreme weather, including droughts, heavy precipitation, heat waves, and intensity of tropical cyclones (U.S. Geological Survey, 2007a).

Natural processes also lead to climate variability and change that occur on all time scales across the Earth. Natural climate variability on multiple time scales (ranging from interannual, multidecadal, and longer geologic-time scales) is a major obstacle to the reliable characterization of global climate change resulting from human activities (Ghil, 2002).

Interannual to multidecadal natural climate variability across the United States is affected by the **El Niño/Southern Oscillation** (**ENSO**), **Pacific Decadal Oscillation** (**PDO**), and **Atlantic Multidecadal Oscillation** (AMO).

**ENSO** is a coupled ocean-atmospheric phenomenon that has interannual variability with irregular 2- to 6-year cycles between the positive (El Niño) and negative (La Niña) phases (fig. 1*A*) (Wolter and Timlin, 1993, 1998). The El Niño generally results in heavy precipitation during winter for parts of the United States, and the La Niña generally results in drier conditions for parts of the United States (Wolter and Timlin, 1993, 1998).

**PDO** is an ENSO-like pattern of Pacific Ocean climate variability that affects winter air temperatures and precipitation in the United States and has interdecadal variability with irregular 10- to 25-year cycles (fig. 1*B*) (Mantua and Hare, 2002). PDO was in the positive phase from 1925 to 1946 and 1977 to 1999 and the negative phase from the late 1890s to 1924 and 1947 to 1976 (fig. 1*B*) (Mantua and Hare, 2002). PDO is currently (2009) in the negative phase, which has been associated with drought conditions across much of the United States (McCabe and others, 2004).

**AMO** is an index of sea-surface temperatures averaged over the North Atlantic Ocean with irregular 70-year cycles (fig. 1*C*) that has a strong influence on summer precipitation and drought frequency in the United States (Enfield and others, 2001). AMO was in the positive phases from 1860 to 1880 and 1930 to 1960, and the negative phases from 1905 to 1925 and 1970 to 1990 (fig. 1*C*). Since 1995, AMO has been in the positive phase, which may result in above-normal frequencies of drought in the United States for the coming decades (McCabe and others, 2004).

## Groundwater Resources

Groundwater is one of the most important natural resources globally. In the United States, groundwater provides much of the Nation's public and domestic water supply, supports agricultural and industrial economies, and contributes flow to rivers, lakes, and wetlands. About 40 percent of the Nation's public water supply is from groundwater in the principal aquifers (fig. 2), and more than 40 million people, including most of the rural population, obtain drinking water from domestic (private) wells (Alley and others, 1999).

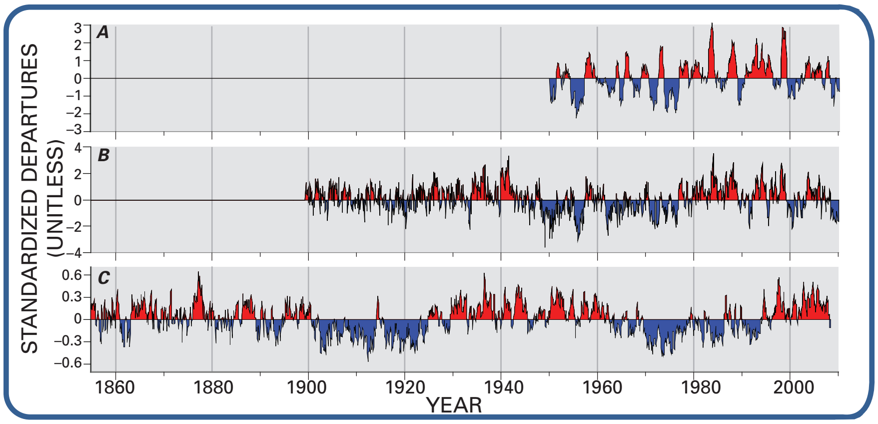

**Figure 1.** Interactions between the positive (red) and negative (blue) phases of the (*A*) multivariate El Niño/Southern Oscillation (ENSO) index (Wolter and Timlin, 1993, 1998), (*B*) Pacific Decadal Oscillation (PDO) index (Mantua and Hare, 2002), and (*C*) Atlantic Multidecadal Oscillation (AMO) index (Enfield and others, 2001) cumulatively affect U.S. climate and, in turn, surface and groundwater resources.

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The availability and sustainability of groundwater in many principal aquifers (fig. 2) is threatened because of depletion by human and climatic stresses (Brekke and others, 2009; Alley and others, 2002). The largely hidden nature of groundwater can result in development that is uncontrolled and not incorporated into river-basin management, which can result in overexploitation and contamination of groundwater. Even without considering climate variability and change, groundwater sustainability is a major challenge because groundwater is a widely distributed resource that is affected by local users and contamination. Additional information about groundwater availability in the United States is summarized by Reilly and others (2008).

## Effects of Climate Variability and Change on Groundwater Resources

Understanding climate variability and change is vital for society and ecosystems, particularly with regard to complex changes affecting the availability and sustainability of surface-water and groundwater resources (Dragoni and Sukhija, 2008). The potential effects of climate variability and change on water resources are well recognized globally and have been identified as a major issue facing the availability of groundwater resources in the United States (Alley and others, 1999).

In recent decades, many scientific studies have improved understanding of the effects of climate change on water resources; however, research has focused primarily on surface water because of the visibility, accessibility, and more obvious recognition of climate effects on surface water than on groundwater (Timothy R. Green, U.S. Department of Agriculture, written commun., 2009). Although recent research has begun to focus more on understanding the effects of climate variability and change on groundwater quantity and quality, the effects remain poorly understood (Green, Bates, and others, 2007; Green, Taniguchi, and Kooi, 2007).

Climate variability and change can affect the quantity and quality of various components in the global hydrologic cycle (Loáiciga and others, 1996; Sherif and Singh, 1999; Milly and others, 2005). The components of the surface hydrologic cycle that may be affected include atmospheric water vapor content, precipitation and evapotranspiration patterns, snow cover and melting of ice and glaciers, soil temperature and moisture, and surface runoff and streamflow (Bates and others, 2008). Such changes to the surface components of the global hydrologic cycle will likely influence the subsurface hydrologic cycle within the soil, unsaturated zone, and saturated zone, and may affect recharge, discharge, and groundwater storage of many aquifers worldwide (Timothy R. Green, U.S. Department of Agriculture, written commun., 2009).

Understanding the potential effects of climate variability and change on groundwater is more complex than with surface water (Holman, 2006). Groundwater-residence times can range from days to tens of thousands of years or more, which delays and disperses the effects of climate and challenges efforts to detect responses in the groundwater to climate variability and change (Chen and others, 2004). Furthermore, human activities, such as groundwater pumping and resulting loss of storage and capture of natural discharge, are often on the same time scale as some climate variability and change, which makes it difficult to distinguish between human and climatic stresses on groundwater (Hanson and others, 2004). For example, the magnitude and phase relation of ENSO, PDO, and AMO cycles may result in average or extreme climate conditions that may affect drought, infiltration, recharge, discharge, and human demand for groundwater resources.

As a result, recent USGS research efforts have characterized subsurface hydrologic and geochemical responses to climate variability on interannual to multidecadal time scales because variability on these time scales has the most tangible implications for groundwater-resource management (Hanson and others, 2004, 2006, 2009; Hanson and Dettinger, 2005; Gurdak and others, 2007). Climate variability on these time scales is often the result of ENSO, PDO, and AMO and can have substantial influence on recharge, discharge, and water-table fluctuations in many aquifers, including the High Plains aquifer (fig. 2) (Gurdak and others, 2007; McMahon and others, 2007; Gurdak, 2008; Gurdak and others, 2009). Response of groundwater levels can be striking when climate variability from ENSO, PDO, and AMO are coincident in a positive or negative phase of variability. Such responses have been identified in aquifer systems of the Southwestern United States (Hanson and others, 2004, 2006) and a number of other aquifers

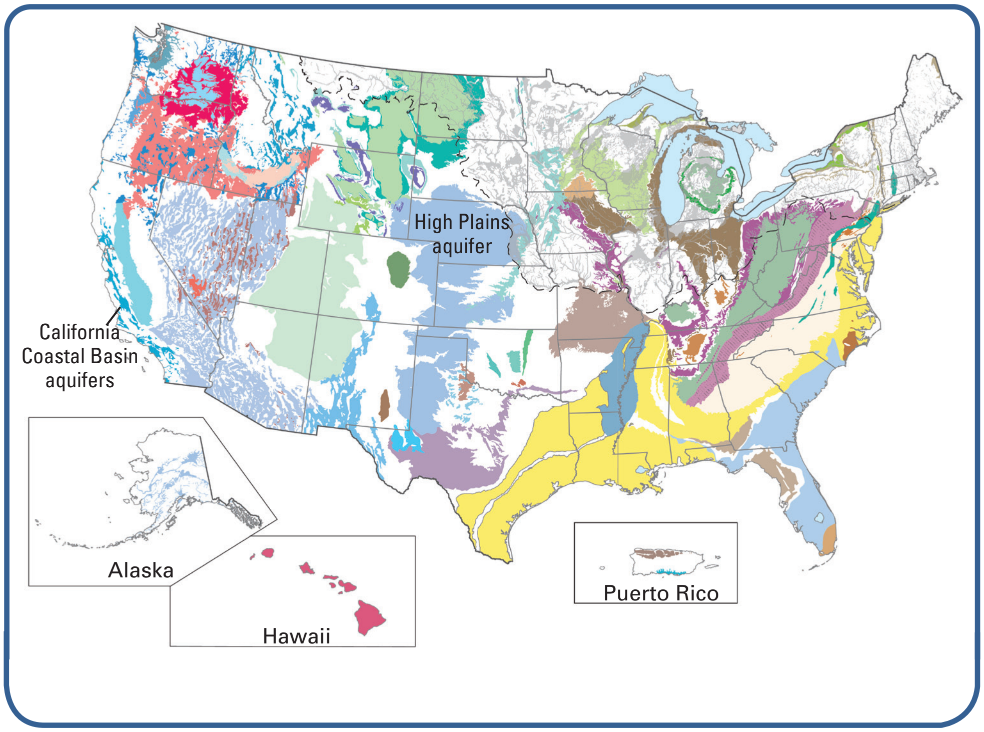

**Figure 2.** Principal aquifers are one of the most important groundwater resources of the United States (modified from U.S. Geological Survey, 2003). The High Plains aquifer underlies parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming and is the most heavily pumped aquifer in the United States (Maupin and Barber, 2005). The California Coastal Basin aquifers, which are present in more than 100 basins in coastal areas of California, are ranked seventh in terms of pumping in the United States (Maupin and Barber, 2005). Explanation of the other principal aquifers is provided in figure 2 of Reilly and others (2008) (available at *http://pubs.usgs.gov/circ/1323/*).

worldwide (Ngongondo, 2006), including those in many small, tropical islands in the Pacific, Indian, and Atlantic Oceans (White and others, 2007). The observed irregular variations in hydrologic time series (such as precipitation, air temperature, streamflow, and groundwater levels) reflect a range of natural and human climate stresses (Hanson and Dettinger, 2005). For example, groundwater levels in the Santa Clara–Calleguas Basin of the California Coastal Basin aquifers (fig. 2) reflect climate variability on time scales that range from days to decades and represent teleconnections between recurrent and persistent climatic patterns over large parts of the Earth's surface, such as ENSO (Hanson and others, 2003).

Although additional research on the topic is needed, climate variability and change can be integral to successful management of groundwater resources (Hanson and others, 2004). Thus, there is a need to evaluate and understand climatic variability and change over the long term to better plan and manage groundwater resources well into the future, while taking into consideration the increasing stresses on groundwater resources from population growth and industrial, agricultural, and ecological needs (Warner, 2007).

## USGS Science Can Help Meet the Challenge

In 2007, the USGS developed a science strategy outlining the major natural science issues facing the Nation in the next decade (U.S. Geological Survey, 2008). The science strategy consists of six science directions of critical importance, including climate variability and change (U.S. Geological Survey, 2007a) and a water census of the United States (U.S. Geological Survey, 2007b). With its long-term observational networks, extensive databases, and diverse scientific expertise, the USGS can provide the broad perspective needed to expand understanding of current climate variability and climate change and their effects on the Nation's water resources (U.S. Geological Survey, 2007a).

The USGS is working with local, State, Federal, and international partners to understand past climate variability and deliver credible future forecasts of climate-change effects on land, water, and ecological and biological resources (U.S. Geological Survey, 2007a). For example, the USGS and U.S. Department of Agriculture are core members of a United Nations project called Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC), in which the High Plains aquifer is the primary case study for North America.

USGS science can help to answer the following critical questions about climate variability and change effects on groundwater resources:

1. How do recharge, discharge, and change in storage in the principal aquifers of the United States (fig. 2) respond to climate variability on interannual to multidecadal timescales and climate change from human activities?
2. Considering future climate change, how much hydrologic response is caused by natural variability and how much is caused by human activities?
3. Do certain time periods of climate variability necessitate time-varying groundwater-management strategies, such as artificial storage and recovery efforts?
4. Are certain principal aquifers more or less susceptible to changes in storage caused by climate variability and change?
5. Can some trends in groundwater quality be linked to climate variability and change?
6. Will the effects of natural climate variability on groundwater resources change over time because of human-induced climate change?
7. What strategic role will groundwater storage play in adapting to climate change?

**Additional information** about USGS science to understand climate variability and change effects on groundwater can be found at the USGS Office of Global Change, Global Change Program Web site (*http://www.usgs.gov/global_change/*) and the USGS Office of Groundwater, Groundwater Resources Program Web site (*http://water.usgs.gov/ogw/gwrp/*).

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For more information concerning this publication, contact:
L. DeWayne Cecil
Chief for Science Applications
USGS Global Change Program Office
Idaho Falls, Idaho 83702
(208) 528-2611

Or visit the USGS Global Science Program Web site at:
*http://www.usgs.gov/global_change*

*—Jason J. Gurdak,[1] Randall T. Hanson,[2] and Timothy R. Green[3]*

[1] U.S. Geological Survey, Colorado Water Science Center, Denver, Colo. Now at San Francisco State University, Department of Geosciences, San Francisco, Calif.

[2] U.S. Geological Survey, California Water Science Center, San Diego, Calif.

[3] U.S. Department of Agriculture, Agricultural Research Service, Fort Collins, Colo.