Impacts of climate variability and changes on groundwater recharge in the semi-arid southwestern United States

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abstract

An understanding of groundwater recharge processes in the semi-arid southwestern United States is essential for the creation of sustainable water and land resource management. Recharge is a function of soil texture, vegetation, the type and locations of preferential flowpaths, and water availability. The spatial and temporal variability of precipitation in the area is influenced by several climate cycles including glacial periods, the Atlantic Multidecadal Oscillation, the Pacific Decadal Oscillation, the North American Monsoon System, and the El Niño-Southern Oscillation. The current semi-arid climate developed about 12,000 years ago, after the end of the most recent ice age. Field and modeling studies show that recharge in the region occurs primarily in drainage areas and is more likely in coarse soils, in unvegetated areas, and when precipitation events are large and occur during periods of cooler temperatures. Variations in groundwater recharge have been correlated by different researchers with cycles of the Pacific Decadal Oscillation and the El Niño-Southern Oscillation. Current modeling of future climate in the southwestern United States projects increased temperatures and decreased precipitation. These changes are likely to result in reduced groundwater recharge in the region, however in the distribution of changed climate parameters, indirect effects of these, and local anthropogenic effects, which are less certain, might largely influence future recharge.

introduction

This paper presents an overview of literature that describes the relationship between groundwater recharge and climate variability in the semi-arid portions of the southwestern United States. I first introduce the region and the general understanding of recharge processes in the area. Next, I define several climate cycles that influence temperature and precipitation in the region and summarize their impact on precipitation. Following this, I describe a number of studies that help to characterize how climate variability influences recharge in the area. Finally, I discuss current projections of climate change over the next century and the implications of these changes on future groundwater recharge. Throughout, I attempt to tie together research findings and past, current, and future trends, with a focus on future groundwater availability.

past and current recharge

Much of the southwestern United States has a semi-arid climate, characterized by the Köppen climate classification system as having low rainfall (between 250 and 500 millimeters per year) and grass or scrub vegetation. The lack of rainfall in these areas typically precludes the development of significant local flow systems and result in thick unsaturated zones through which water must travel to reach the water table.

Understanding recharge processes in semi-arid regions of the southwestern United States and around the world is essential to estimating groundwater availability and to assessing the risk of groundwater contamination. Further, these processes can vary significantly in time and space, which has important implications for water and land use planners interested in sustainable resource management and development.

Calculations of groundwater systems for modeling and resource management have often used an estimate of long-term average annual recharge as the input to the system. However, this seems increasingly an inadequate measure, both because it does not accommodate our full understanding of recharge processes and because it does not allow for an assessment of how climate and land use changes might affect groundwater availability (Hanson and others 2004, Pool 2005).

Recharge can be defined by a water-balance equation

$$R = P + I - ET - RO \qquad (1)$$

where R is recharge, P is precipitation (a function of climate parameters), I is irrigation water (a function of land use, crop type, climate, and irrigation technique), ET is evapotranspiration (a function of climate, vegetation, and soil parameters), and RO is runoff (a function of slope, soil, and vegetation parameters). These variables are functions of climate and weather parameters, soil, vegetation, irrigation techniques, land use, slope, and other factors.

For the purposes of this discussion, I equate recharge to infiltration below the root zone. This definition assumes that once water has infiltrated below the area where it can be evaporated or transpired, it will eventually reach the water table. In addition, recharge can be characterized as diffuse—infiltrating through the soil matrix in interdrainage areas—or focused—infiltrating through drainage areas or other preferential flow paths.

In addition to effects of climate variability, the primary focus of this review, previous studies have identified recharge-controlling mechanisms in the semi-arid southwestern United States. They have found that recharge is more likely to occur

- in topographic depressions where precipitation is likely to collect, such as playas and ephemeral streams (Scanlon and Goldsmith 1997, Pool 2005)
- in areas where soils at the surface are coarse-grained (Gee and others 1994, Scanlon and others

2003)

- through preferential flow paths, such as cracks or along roots (Scanlon and Goldsmith 1997, Scanlon and others 2003)
- where rooting depths are shallow, or, even more likely, where there is no vegetation (Gee and others 1994, Scanlon and others 2005a)
- in irrigated areas (Scanlon and others 2005b)

Study results indicate that in general, interdrainage areas in the southwestern United States commonly have no recharge or even upward fluxes of water. While the characteristics described above help define whether a given area is likely to allow downward infiltration of water, the primary limiting characteristic in this region (except for in irrigated areas) is the availability of precipitation to infiltrate. Therefore, it is important to identify variations in precipitation, the climate patterns that drive these variations, and how these patterns change over time. For water and land use planners, the ability to predict likely future changes in precipitation on short and long time scales could significantly increase the sustainability of management policies.

past and current climate cycles

Although the semi-arid climate of the southwestern United States can be generally described as above, this climate is temporally and spatially variable on many scales. On a large scale, climate variability in these areas is driven by a number of cyclical atmospheric and oceanic phenomena that occur on different timescales. These phenomena, and their relationships to climate in the southwestern United States, are described below in order of decreasing cyclicity.

Large-scale climate changes occur over thousands or millions of years, as the global climate shifts from glacial to interglacial periods and as continental plates move. Studies indicate that the current climate and native vegetation in the southwestern United States was established after the most recent glacial period, 10,000 to 15,000 years ago (Scanlon and others 2005a).

The **Atlantic Multidecadal Oscillation (AMO)** is an oscillation of sea surface temperatures in the North Atlantic Ocean that has a period of around 65-80 years. Over most of the continental United States, warm phases of the AMO are associated with below average precipitation, primarily in the summer (Enfield and others 2001). McCabe and others (2004) found that the AMO, along with the Pacific Decadal Oscillation (discussed below), can explain most of the variability in multidecadal droughts over the continental United States, with positive AMO phases associated with dry conditions. In addition, the cycle appears to explain some of the interannual rainfall related to the El Niño-Southern Oscillation (discussed below) (Enfield and others 2001).

The **Pacific Decadal Oscillation (PDO)** is a multidecadal, cyclical variation in sea surface temperatures in the Pacific Ocean north of 20° latitude (McCabe and Dettinger 1999). Although the mechanism for this cycle is not well understood, the PDO has been related to climate variability in the southwestern United States over one or more decades. In general, warm PDO phases are correlated with higher amounts of precipitation in the region (Mantua and Hare 2002) and cold phases are associated with drought (McCabe and others 2004). In addition, the influence of the El Niño-Southern Oscillation (ENSO) (discussed below) on precipitation in the western United States appears to depend in part on the PDO—during warm PDO phases ENSO is likely to show a weak connection to precipitation, while during cold PDO phases ENSO is likely to be strongly connected to precipitation (McCabe and Dettinger 1999).

The **North American Monsoon System (NAMS)** is a system that moves north from

Mexico to New Mexico and Arizona during the spring and summer and that is thought to largely control interannual variations in summer precipitation in the central United States. The timing of the NAMS corresponds to similar wet conditions along the east coast of the United States and to dry conditions over the Great Plains. The strength of this pattern over North America seems to be linked to the strength of the NAMS anticyclone. Thus, dry NAMS years are associated with dry years along the east coast and wet years over the Great Plains (Higgins and others 1998). While the cause of the strength of the NAMS is not well understood (Hanson and others 2004), variability in the system has been correlated with sea surface temperatures and atmospheric conditions within the Intertropical Convergence Zone (ITCZ) on the eastern Pacific, with wet NAMS years occurring in years of low precipitation near the equator. These same years are associated with local suppressed Hadley circulation (Higgins and others 1998).

The **El Niño-Southern Oscillation (ENSO)** is a phenomenon that occurs in the equatorial Pacific Ocean and causes interannual climate variability in low and middle latitudes. Under normal conditions, the ocean temperature in the Pacific grades from warm in the west to cold in the east—westward-blowing trade winds help to keep this warm water in the west. Every several years, these winds subside, the east-west pressure gradient decreases, and warm water moves east to South America, causing sea surface temperatures there to rise. This is called an El Niño event (Hartmann 1994, 187 need more complete source) and is associated with abnormally cool winter temperatures and high winter precipitation in the southwestern United States (Scanlon and others 2005a). At other times, cold sea surface temperatures and a strong east-west pressure gradient exist along the South American coast. These conditions are known as La Niña events (references in Pool, 2005) and are associated with warm winter droughts (Scanlon and others 2005a) followed by wet summer monsoons in the southwestern United States. The strength of this association varies and is in part explained by variations in the PDO, as discussed above (McCabe and Dettinger 1999).

effects of documented climate variability on recharge

A number of recent studies have begun to assess how groundwater recharge in the semi-arid southwestern United States is impacted by climate variability. These studies address the impacts of specific climate or climate-related variables, such as the distribution of precipitation or vegetation, on recharge rates. In addition, several of these have compared variations in recharge rates with oscillations in the climate cycles discussed above.

At the millenial scale, studies have used environmental tracers and geologic proxies to detect the shift from a cooler and wetter climate to the semi-arid climate of today, with associated changes in vegetation and geomorphology, in the southwestern United States that occurred around the Pleistocene-Holocene boundary (about 12,000 years ago). One of the types of evidence for this change comes from profiles of chloride concentrations and water content in soil cores. If recharge does not occur, chloride deposited by wind and rain will build up near the surface, creating large bulges of high chloride concentrations. In addition, soil water content beneath the root zone will slowly dry out. Models indicate that thousands of years without flushing by recharge are required to replicate the chloride bulges and upward water potential gradients shown in cores from the semi-arid southwestern U.S. (Scanlon and others 2003, Seyfried and others 2005).

In order to assess how variations in precipitation and potential evapotranspiration affect diffuse groundwater recharge in semi-arid regions, Small (2005) used one-dimensional unsaturated flow modeling with inputs based on typical field conditions and climate records. His results indicated that recharge occurs above a threshold precipitation rate—this threshold is decreased with coarser soil texture, larger storm size, and lower potential evapotranspiration. Thus, climates characterized by fewer but larger storms will be more likely to have diffuse recharge than those characterized by more but smaller storms. In addition, climates in which the rainy season occurs during the winter, when evapotranspiration is low, will be more likely to have diffuse recharge. Field observations and modeling by Scott and others (2000) support this conclusion, finding that the deepest infiltration occurs during winters with high precipitation. These studies illustrate the importance of understanding climate variability, and not only average temperatures and evaporation rates, in order to characterize recharge processes.

An important conclusion of several studies is that the dynamic response of vegetation to short and long-term changes in climate within semi-arid regions appears to significantly control the water cycle. Data indicate that in general, the presence of native vegetation and ecosystems prevent water from infiltrating beyond the first few meters of the unsaturated zone. These studies suggest that interannual climate variations can have negligible results on recharge in interdrainage areas. However, these studies also suggest that where vegetation is absent or where non-native species are present, deeper infiltration is possible. These conditions could result from non-native species invasions; conversion of native vegetation to cropland, which lies fallow for the coldest months of the year; vegetation that becomes dormant in winter months; or fires (Gee and others 1994, Scott and others 2000, Scanlon and others 2005a, Seyfried and others 2005).

Recent studies have attempted to more directly associate the relationships between between changes in groundwater storage (reflected in gravity or water level changes), precipitation, and the climate cycles discussed above. Scott and others (2000) used field observations and modeling to show that deep infiltration occurs during high precipitation winters that they associated with El Niño. Hanson and others (2004) used a novel frequency analysis method to show that variability in groundwater levels and streamflow records from southern California correlate to changes in the PDO and ENSO. Pool (2005) found that precipitation records in a semi-arid region in southern Arizona showed winter and spring precipitation amounts, but not summer and fall precipitation amounts—were correlated with ENSO events. Further, their research showed that the likelihood of winter streamflow and recharge in ephemeral channels increases during El Niño events. They also note that higher recharge rates are associated with warm PDO phases.

In contrast, Hanson and others (2006), using the method of Hanson and others (2004), found that PDO timescales explained the most variation in hydrologic records for four basins in California and Arizona. In addition, both ENSO and NAMS timescales contributed to the variation, although the NAMS timescales showed a greater influence in the Arizona basins than in those in California. More recently, Gurdak and others (2007) found precipitation over the High Plains could be mostly explained by cycles of the PDO and longer and that groundwater levels were primarily influenced by PDO forcings, followed by NAMS, ENSO, and annual cycles. Their field data clarify that significant infiltration results from exceptionally high precipitation rates over a few months and appear to occur as focused recharge.

There fact that some of the studies described above attribute hydrologic variability to different climate cycles is likely the result of different study areas, datasets, and time periods of interest; the increasing amount and quality of data; new methods of analysis; and an improved understanding of the cycles, in particular the PDO. Future research is needed to better characterize the relationships between recharge, climate, and vegetation dynamics in the region. In addition, many other climate parameters, such as wind speed and direction, can influence groundwater recharge in ways not discussed here.

projected future climate changes

For those interested in the sustainability of water and land resources, perhaps the most important implication of the research discussed above is its relevance to predicting climate variability and change in the coming decades and centuries. In water-limited climates, especially those with growing populations and water demands, even small changes in temperature and precipitation patterns can have significant impacts on water resources. While this topic has been addressed for several decades, an increasing number of academic and popular press articles are discussing projections from multiple sources of a shift to a more arid climate in the southwest United States (for example, Revelle and Waggoner 1983, Enfield and others 2001, Gertner 2007, Seager and others 2007).

Probably the most up-to-date and thorough assessment of projected future global climate change is documented in the latest report of the Intergovernmental Panel on Climate Change, released earlier this month (Christenson and others 2007). This assessment includes the results of 21 Atmospheric-Ocean General Circulation Models (GCMs) for a variety of possible future scenarios over the next century. For the southwestern United States, the report projects the following *likely* changes:

- an average increase in temperature that exceeds the average global increase and is greatest during the summer;
- an increase in the probability of longer, more intense hot spells during the summer; and

- a decrease in precipitation.[*]

In addition, the report contains several other relevant *likely* conclusions:

- increased precipitation globally is likely to lead to increased variability in precipitation over the mid-latitudes in the northern hemisphere;
- the frequency of extreme precipitation events is likely to increase in the mid-latitudes;
- the length of the snow season and depth of snow is likely to decrease throughout North America;
- possible abrupt changes, for example those from a significant change in ocean circulation, are not addressed in the modeling because researchers are unable to estimate the probability of these events; and
- the models do not agree on what possible changes might occur in ENSO as a result of climate change.

Clearly, a regional-scale model that could provide more specific projections and clarify uncertainties described above would give a better picture of the likely future climate in the southwestern United States. However, current regional climate models of North America use time spans that are not long enough to represent all the temporal cycles discussed above and do not provide consistent or significant additional information (Christenson and others 2007).

possible effects of future climate on recharge

GCMs and the data they use are becoming increasingly robust and their outputs are viewed with increasing confidence (Christensen and others 2007). However, one of the

[*] Data in one table of this report appears to indicate increased precipitation across the United States, conflicting with this statement. However, the statement is confirmed in several places in the text and in figures. I presume the apparent disagreement is due to a misunderstanding on my part or to an error in this (possibly still draft) document.

characteristics of these models is that they have a grid size of around 200 km and thus cannot accurately simulate climate changes on the smaller scales that are essential to water resource studies (Xu 1999). Regional climate models and methods of downscaling GCM outputs are advancing (Christenson and others 2007), but significant improvements are needed for use in water resources planning.

Predictions of how a warmer climate might affect water supplies in the southwestern United States date to at least the early 1980s. For example, Revelle and Waggoner (1983) used available climate and hydrologic records to predict a severe reduction in water quantity and quality under a scenario of increased temperature and decreased precipitation caused by increased atmospheric concentrations of CO_2. More recently, McCabe and others (2004) assessed records of climate and drought in the United States and predicted an increasing frequency of drought in coming decades resulting primarily from positive AMO conditions, and noted the relevance of this finding to water resources in the western United States.

Fewer studies have focused on possible changes in recharge as a result of projected climate change. A study by Rosenberg and others (1999) used output from three climate models to predict how projected changes in precipitation, temperature, and atmospheric CO_2 concentrations might affect groundwater recharge to the Ogallala aquifer, which underlies much of the west-central United States. In addition to accounting for the precipitation and temperature changes, the modeling estimated the effect of increased CO_2 levels on plant growth—that is, the tendency for plants to grow more quickly, larger, and with less water in air with higher CO_2 concentrations. However, despite this reduced water use and despite increased precipitation in one of the model projections used, the modeling resulted in decreased recharge throughout the Ogallala aquifer.

Based on the research discussed above, I propose some general speculative statements about how groundwater recharge might be affected by projected climate changes. First, the IPCC projections of increased temperature and decreased precipitation in the southwestern United States (Christenson and others 2007) provide a strong case for a future reduction in recharge. Even with unchanged precipitation rates, higher temperatures would increase evaporation and reduce the potential for recharge. Decreased precipitation would probably result in the added impact of reduced streamflow. In support of this conclusion, recharge studies that had study sites in dry climates at multiple latitudes (for example, Gee and others 1994, Gurdak and others 2007) found higher rates of downward water fluxes in the higher latitude, cooler sites with similar precipitation rates.

Second, a major lesson from many of the studies described above is that the timing and variability of temperature and precipitation at a given semi-arid location can play an important role in whether or not recharge takes place. Thus, more detailed information on the projected climate changes would greatly strengthen an assessment of the future potential for recharge. For example, if precipitation was reduced, but the timing changed so that nearly all rain events were large and occurred at night during the winter, this reduction in precipitation might well lead to increased recharge. In addition, it would be helpful to have information on projected changes in vegetation resulting from climate change. An increased frequency of wildfires or invasion of less well-adapted, shallower-rooted plants might allow more water (perhaps of poorer quality) to infiltrate.

Third, overall recharge, as input to groundwater systems, is significantly affected by local anthropogenic factors. The change from natural rangelands to agricultural fields in the southwestern United States can increase recharge as a result of decreased rooting depths, winter fallow periods where there is no vegetation cover, and applied irrigation water (Scanlon and others 2005b). Heavy groundwater pumping for irrigation or municipal supplies can cause the water table to decline at a rate faster than water can infiltrate through the unsaturated zone. In addition, manmade recharge enhancement structures or other intentional manipulations of the land surface can be used to increase (or decrease) the potential for recharge.

conclusions

This paper provides a summary of the current knowledge of groundwater recharge and its relationship to climate variability in the southwestern United States. The research presented indicates that variability in precipitation and temperature, as well as responses of vegetation to these variations, creates complex recharge processes in semi-arid climates. Given this, current projected climate changes leave many questions remaining for those interested in the sustainable use of land and water resources. However, the current understanding of recharge processes allows for some assessment and for provides a framework for designing future research. In addition, the amount of recent literature available on these topics shows that this is an active area of research and that the ability of land and water managers to plan for a changing climate will continue to improve.

references

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R. K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C. G., Räisänen, J., Rinke, A., Sarr, A., and Whetton, P., 2007, Regional climate projections *in* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H.

L., editors, Climate change 2007—The physical science basis—Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change: New York, New York, United States, Cambridge University Press.

Enfield, D. B., Mestas-Nuñez, A. M., and Trimble, P. J., 2001, The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S.: Geophysical Research Letters, v. 28, no. 10, p. 2077-2080.

Gee, G. W., Wierenga, P. J., Andraski, B. J., Young, M. H., Fayer, M. J., and Rockhold, M. L., 1994, Variations in water balance and recharge potential at three western desert sites: Soil Science Society of America Journal, v. 58, p. 63-72.

Gertner, J., October 21 2007, The future is drying up: The New York Times, section 6, column 0, p. 68.

Gurdak, J. J., Hanson, R. T., McMahon, P. B., Bruce, B. W., McCray, J. E., Thyne, G. D., and Reedy, R. C., 2007, Climate variability controls on unsaturated water and chemical movement, High Plains Aquifer, USA: Vadose Zone Journal, v. 6, no. 2, p. 533-547.

Hanson, R. T., Dettinger, M. D., and Newhouse, M. W., 2006, Relations between climatic variability and hydrologic time series from four alluvial basins across the southwestern United States: Hydrogeology Journal, v. 14, p. 1122-1146.

Hanson, R. T., Newhouse, M. W., and Dettinger, M. D., 2004, A methodology to assess relations between climatic variability and variations in hydrologic time series in the southwestern United States: Journal of Hydrology, v. 287, p. 252-269.

Hartmann, D. L., 1994, Global physical climatology: San Diego, California, United States, Academic Press, 411 p.

Higgins, R. W., Mo, K. C., and Yao, Y., 1998, Interannual variability of the U.S. summer precipitation regime with emphasis on the Southwestern Monsoon: Journal of Climate, v. 11, no. 10, p. 2582-2606.

McCabe, G. J., and Dettinger, M. D., 1999, Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States: International Journal of Climatology, v. 19, p. 1399-1410.

McCabe, G. J., Palecki, M. A., and Betancourt, J. L., 2004, Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States: Proceedings of the National Academy of Sciences USA, v. 101, no. 12, p. 4136-4141.

Pool, D. R., 2005, Variations in climate and ephemeral channel recharge in southeastern Arizona, United States: Water Resources Research, v. 41, p. W11403, 24 p., doi:10.1029/2004WR003255.

Revelle, R. R., and Waggoner, P. E., 1983, Effects of a carbon-dioxide-induced climatic change on water supplies in the western United States, *in* Council, U. S. N. R., ed., Changing climate—Report of the Carbon Dioxide Assessment Committee: Washington, D.C., National Academy Press, p. 419-432.

Rosenberg, N. J., Epstein, D. J., Wang, D., Vail, L., Srinivasan, R., and Arnold, J. G., 1999, Possible impacts of global warming on the hydrology of the Ogallala aquifer region: Climatic Change, v. 42, p. 677-692.

Scanlon, B. R., and Goldsmith, R. S., 1997, Field study of spatial variability in unsaturated flow beneath and adjacent to playas: Water Resources Research, v. 33, no. 10, p. 2239-2252.

Scanlon, B. R., Keese, K., Reedy, R. C., Simunek, J., and Andraski, B. J., 2003, Variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing (0-90 kyr)—Field measurements, modeling, and uncertainties: Water Resources Research, v. 39, no. 7, p. 1179 doi:10.1029/2002WR001604.

Scanlon, B. R., Levitt, D. G., Keese, K. E., Reedy, R. C., and Sully, M. J., 2005a, Ecological controls on water-cycle response to climate variability in deserts: Proceedings of the National Academy of Sciences USA, v. 102, p. 6033-6038.

Scanlon, B. R., Reedy, R. C., Stonestrom, D. A., Prudic, D. E., and Dennehys, K. F., 2005b, Impact of land use and land cover change on groundwater recharge and quality in the southwestern US: Global Change Biology, v. 11, no. 10, p. 1577-1593.

Scott, R. L., Shuttleworth, W. J., Keefer, T. O., and Warrick, A. W., 2000, Modeling multiyear observations of soil moisture recharge in the semiarid American Southwest: Water Resources Research, v. 36, no. 8, p. 2233-2247.

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Huang, H.-P., Harnik, N., Leetmaa, A., Lau, N.-C., Li, C., Velez, J., and Naik, N., 2007, Model projections of an imminent transition to a more arid climate in southwestern North America: Science, v. 316, p. 1181-1184.

Seyfried, M. S., Schwinning, S., Walvoord, M. A., Pockman, W. T., Newman, B. D., Jackson, R. B., and Phillips, F. M., 2005, Ecohydrological control of deep drainage in arid and semiarid regions: Ecology, v. 86, no. 2, p. 277-287.

Small, E. E., 2005, Climatic controls on diffuse groundwater recharge in semiarid environments of the southwestern United States: Water Resources Research, v. 41, p. W04012, doi:10.1029/2004WR003193.

Xu, C.-Y., 1999, Climate change and hydrologic models—A review of existing gaps and recent research developments: Water Resources Management, v. 13, p. 369-382.