Spring 2006

A Delicate Balance: Rainfall and Groundwater in Nebraska During the 2000-2005 Drought

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Great Plains Research 16 (Spring 2006): 5-16

A DELICATE BALANCE: RAINFALL AND GROUNDWATER IN NEBRASKA DURING THE 2000-2005 DROUGHT

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ABSTRACT—Recent decreases in rainfall and the accompanying decreases in groundwater levels since 1999 indicate heightened vulnerability to drought in Nebraska and the surrounding Great Plains. Precipitation across Nebraska during 2000-2005 ranged from 72% to 108% of the 30-year normal value, with fully 90% of 150 stations reporting below-normal precipitation. Simultaneously, groundwater levels declined more than 9 m in the most heavily impacted areas, most of which were already experiencing declines due to extensive irrigation development and low recharge rates. Thus, recovery from the drought and long-term intensive land use will be particularly challenging in densely irrigated areas of Nebraska. In contrast, contemporaneous groundwater-level changes in areas with little groundwater irrigation were comparatively modest. These observations demonstrate that drought mitigation efforts in the central and northern Great Plains must consider the combined effects of area-specific reduced recharge, local geohydrology (especially as it affects recharge), and increased groundwater withdrawals.

Key Words: climate impacts, drought, groundwater levels, groundwater monitoring, vulnerability

INTRODUCTION

Droughts affect more people worldwide than any other natural hazard (Hewitt 1997; Wilhite 2000). In the United States, the central and northern Great Plains is particularly prone to drought (Karl et al. 1987; Soulé 1993; Woodhouse and Overpeck 1998), and indeed, major parts of the Great Plains are currently (January 2006) experiencing a multi-year drought. Major socioeconomic impacts have accompanied historic droughts in the Great Plains (e.g., Worster 1979), and therefore it is likely that the current drought will have similar effects. In view of the potentially large impact of drought on Great Plains groundwater resources, we seek in this paper to (1) characterize the nature of drought in the northern Great Plains, (2) document groundwater-level changes associated with the ongoing drought in Nebraska, (3) identify regions that may be particularly vulnerable to hydrological drought, and (4) offer insights into the hydrogeological consequences of long-term drought in Nebraska and some adjacent areas.

Various climate records and climate-proxy records indicate that severe drought has been a recurrent phenomenon in North America for millennia (e.g., Woodhouse and Overpeck 1998; Alverson et al. 2003; Guyette et al. 2004; Knapp et al. 2004). In the contiguous United States, drought tends to be most persistent in the central Great Plains (Kansas, Nebraska, and eastern Colorado) to northern Great Plains (South Dakota, North Dakota, eastern Wyoming, and east-central Montana) and Rocky Mountains (Walsh et al. 1982; Karl 1983; Karl et al. 1987; Soulé 1992). The recent drought in the Great Plains (2000-2005) has dramatically affected a major portion of the nation's land area. In Colorado, for example, 2002 was the driest year since 1890: the majority of the state received less than 70% of average yearly precipitation (NCDC 2003; Pielke et al. 2005). In Wyoming and Nebraska, 2002 was the third driest year in the 108-year record (NCDC 2003). The Nebraska Sandhills, which occupy a full 25% of the state's land area, have recently been shown to be especially vulnerable to drought (Loope and Swinehart 2000; Mason et al. 2004; Nicholson and Swinehart 2005).

Five years of ongoing drought have resulted in serious economic, social, and environmental impacts across the affected area, and the drought has received extensive press coverage. Even more importantly, the drought has also raised serious concerns about the region's future vulnerability to drought-induced water shortages and the viability of existing human land-use and settlement patterns (e.g., White 1994; Vörösmarty and Sahagian 2000; Peterson et al. 2003; Polsky 2004).

In 1995 the Federal Emergency Management Agency (FEMA) estimated that droughts in the United States cause an average annual economic loss of $6 to $8 billion, or $7.5 to $10 billion in 2005 dollars (FEMA 1995). Estimates of drought's economic impact in 2002 alone range from $10 billion (NCDC 2005a) to more than $20 billion (Wilhite 2005). In 2002, estimates of agricultural losses on the Great Plains ranged from $1.1 billion in Colorado to $2.0 billion in Montana (Hayes et al. 2004). On a per capita basis in 2002, the four states spending the most to recover from extreme weather events were all located in the northern Great Plains: North Dakota, South Dakota, Nebraska, and Wyoming (US PIRG Education Fund 2003). The expenditures were primarily in the form of insurance claims and government emergency loans and disaster relief funds. Total economic drought losses for the entire recent drought period are certainly much higher (Hayes et al. 2004).

It is particularly notable that the drought spurred a dramatic increase in irrigation well drilling in heavily impacted Great Plains states. In 2005 Montana granted the largest number of groundwater appropriations for irrigation in nearly two decades (MDNRC 2006). In 2002 Wyoming granted the largest number of groundwater irrigation well permits in 12 years for eight Great Plains counties (Albany, Converse, Carbon, Natrona, Niobrara, Platte, Goshen, and Laramie). The period 2001-2005 also saw the most irrigation well permitting in Wyoming over a five-year period since the late 1970s (WSEO 2006). Similarly, in Colorado, during the period 2000-2004 the largest number of irrigation well permits was granted in a five-year period since the 1970s (Colorado Department of Water Resources 2006 unpublished data). In Nebraska, the number of irrigation wells registered in 2002 was a single-year record (NDNR 2006). As a consequence of the abundance of irrigation wells, declining stream levels, and declining groundwater levels, many portions of Nebraska are now classified as fully appropriated or overappropriated (NDNR 2006). Similarly, portions of southwestern Kansas have been closed to additional appropriations for several decades (McGuire et al. 2003).

As determined by the U.S. Drought Monitor (NDMC 2005), severe drought conditions were evident by the spring of 2000 in parts of the Great Plains (Fig. 1). The Drought Monitor summary map identifies general drought areas, labeling droughts by intensity, with D1 being the least intense and D4 being the most intense. "Drought" means a moisture deficit severe enough to have social, environmental, or economic effects, and therefore the Drought Monitor also includes a description of whether the primary physical effects are to agriculture and/or water supplies. Drought conditions quickly spread, encompassing the entire central and northern Great Plains over the next five years. Severe to extreme drought conditions continued over much of the central and northern Great Plains in the spring of 2005 (Fig. 1). In Nebraska, moderate drought persisted in the western and southern parts of the state at the time this paper was revised (January 2006).

Water-level measurements from observation wells are the principal source of information about the effects of hydrologic stresses on groundwater systems (Taylor and Alley 2001). During times of severe drought this hydrologic stress is most acute. Watershed response to drought is variable, depending on such factors as precipitation, evapotranspiration, soil/geologic properties, land-use practices, runoff, and withdrawals. Drought and subsequent withdrawals from high production wells, however, can have a rapid and large impact on groundwater levels (Neilson and Bearce 1998; Butterworth et al. 1999; Wendland 2001).

DROUGHT: CHARACTERIZATION AND DEFINITIONS

Drought is a slow-onset phenomenon that may take months to develop and may persist through several seasons or multiple years. By its very nature, drought is a complex phenomenon with manifold effects. There are currently a number of different schemes used to characterize droughts, and each scheme incorporates different combinations of physical, biological, and socioeconomic variables. Droughts are typically grouped into four types. *Meteorological* or *climatological drought* is defined in terms of the departure from normal precipitation and the duration of the event. *Agricultural drought* is defined by linking the various characteristics of meteorological drought to agricultural impacts, focusing largely on the consequences of soil-moisture deficits and subsequent impacts on crops. The concept of *hydrological drought* concentrates on the effects of periods of precipitation shortfall on surface or subsurface water supply, rather than with precipitation shortfalls directly. The onset of hydrological drought typically follows the developments of meteorological and agricultural drought because of time

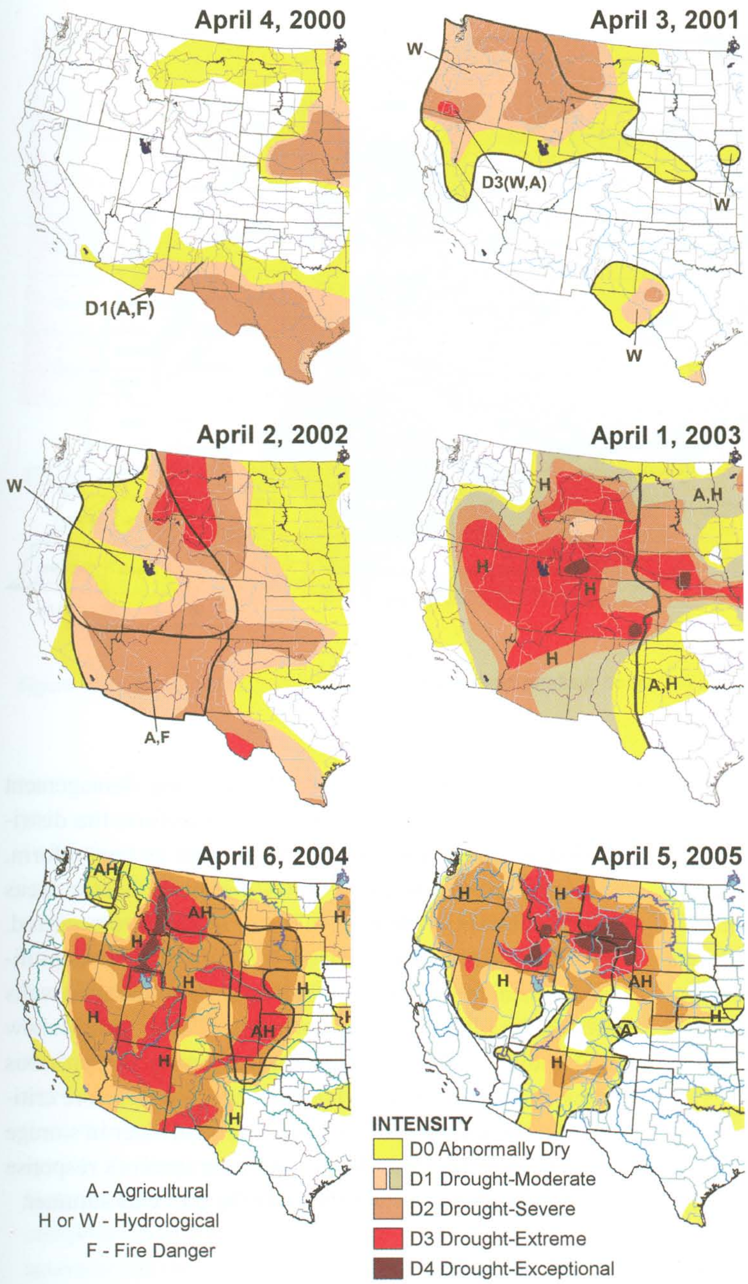

Figure 1. Drought intensity in the western United States, spring 2000 to spring 2005. Heavy black lines delineate dominant impact areas; blue lines refer to major rivers; and light gray lines refer to boundaries of climate divisions, groups of counties within each state that should have similar climate. (Source: Drought Monitor, National Drought Mitigation Center).

lags associated with the response of surface water and groundwater systems to temporal changes in precipitation. According to Heim (2002), "*socioeconomic drought* associates the supply and demand of some economic good with elements of meteorological, agricultural, and hydrological drought. It differs from the aforementioned types of drought because its occurrence depends on the time and space processes of supply and demand to identify or classify droughts." In this paper, we are concerned chiefly with hydrological drought.

THE DROUGHT OF 2000-2005 IN NEBRASKA AND ITS RELATIONSHIP TO GROUNDWATER

The current drought in the central and northern Great Plains began in October 1999 when the U.S. Drought Monitor reported exceptionally dry conditions in the eastern half of Nebraska (NDMC 2005). By the spring of 2000 conditions had deteriorated and two-thirds of Nebraska was experiencing severe drought (Fig. 1). By the spring of 2002 the drought encompassed the entire central and northern Great Plains. The drought appears to have reached its zenith in 2002. According to the National Climate Data Center (NCDC 2003), "Nebraska was the epicenter of drought in the central Plains [in 2002]. Precipitation shut off over much of the state beginning in December 2001, resulting in the driest December-July in the 108-year record." As of January 2006 much of Nebraska continues to experience abnormally dry to moderate drought conditions.

Groundwater supply and demand are intimately linked to long-term drought in Nebraska and surrounding Great Plains states. The High Plains aquifer underlies more than 80% of the High Plains and supplies drinking water for 82% of the 2.3 million people who live within the region (Scholle and Allison 2002). Ninety-four percent of groundwater withdrawals from the aquifer are for irrigation (Hutson et al. 2004), a volume totaling about 30% of the nation's groundwater used for irrigation (Scholle and Allison 2002). Thus, the High Plains aquifer is the most intensely pumped regional aquifer in the United States, and in general, recharge of the aquifer has not compensated for withdrawals since major irrigation development began in the 1930s (Rosenberg et al. 1999; McGuire et al. 2003; McGuire 2004).

In Nebraska, groundwater is primarily used for irrigation, but it is also the major contributor to municipal, domestic, and industrial supplies. Groundwater irrigation in

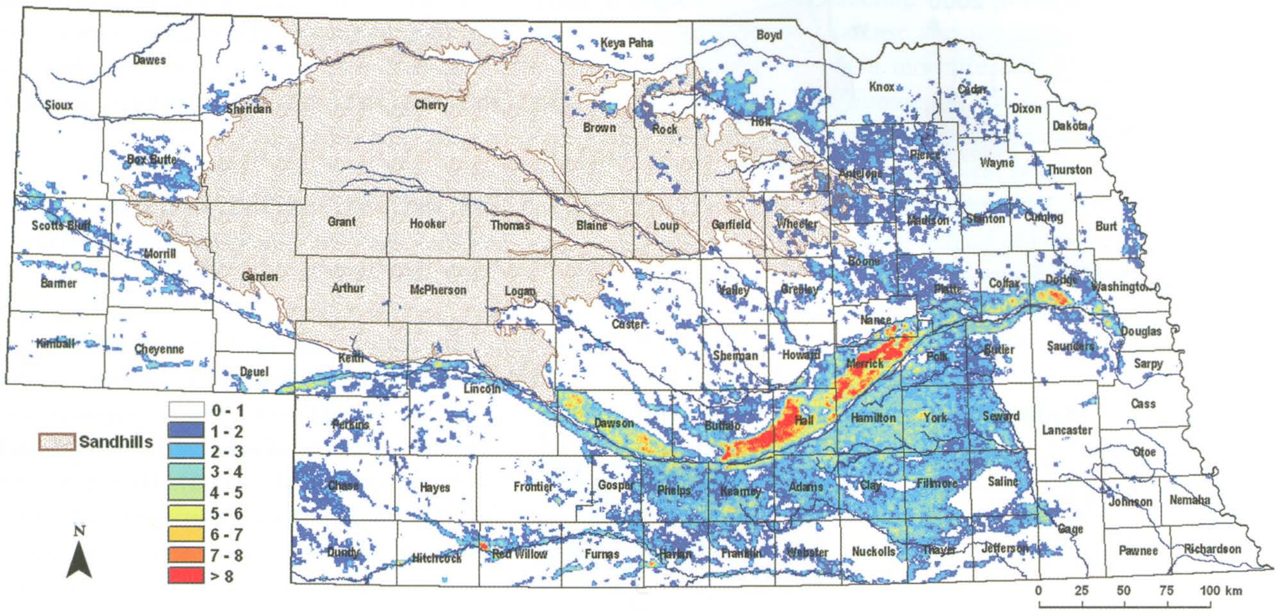

Figure 2. Density in wells per square kilometer of registered irrigation wells in Nebraska, August 2005.

Nebraska in 2000 consumed about 7.4 billion gallons (28 billion liters) per day, or nearly 94% of total withdrawals (Hutson et al. 2004). The distribution of irrigation wells in Nebraska is extremely dense in many regions (Fig. 2). Groundwater is also important for domestic, commercial, and industrial purposes in Nebraska. Eighty-one percent of Nebraska's public water supply comes from groundwater and 100% of private supplies are derived from groundwater, compared to less than 40% nationally (Hutson et al. 2004).

GROUNDWATER MONITORING IN NEBRASKA

In 1930 the Conservation and Survey Division of the University of Nebraska–Lincoln and the U.S. Geological Survey began a cooperative water-level measurement program to observe and document the changes in groundwater levels throughout Nebraska. This continuing program includes evaluation of the adequacy and accuracy of the water-level information collected and provides a means for data storage, retrieval, and dissemination. More than 5,000 observation wells monitored by 26 federal, state, and local agencies are currently used to monitor groundwater levels in Nebraska. All the wells are measured in the spring and about one-half are also measured in the fall.

The data from the groundwater-level program are used to determine annual and long-term water-level changes. Water-level measurements are made for a variety of reasons such as forecasting trends, assessing management programs, and resource evaluation; therefore, the distribution of observation wells in the state is nonuniform. The greatest densities of wells measured are in areas where substantial changes in water levels have occurred. Because use of water for irrigation causes the most significant substantial water-level fluctuations, observation wells are measured in the spring when water levels should show maximum recovery from pumping during the previous growing season. Spring measurements are therefore critical in determining the amounts of groundwater in storage prior to irrigation and the groundwater system's response to large groundwater withdrawals the previous summer.

METHODOLOGY

Precipitation data were collected from 106 weather stations across Nebraska and 44 stations immediately adjacent to the state's borders during the period 2000-2005 (NCDC 2005b). Precipitation deficits or surpluses for the study period, expressed as a percentage of normal, were determined by dividing the five-year precipitation total at a particular weather station by the five-year normal precipitation for that station and then multiplying by 100. The five-year normal precipitation was calculated by multiplying "normal" annual precipitation for a particular weather station by five. Normal precipitation is considered the average precipitation for a 30-year period. The most

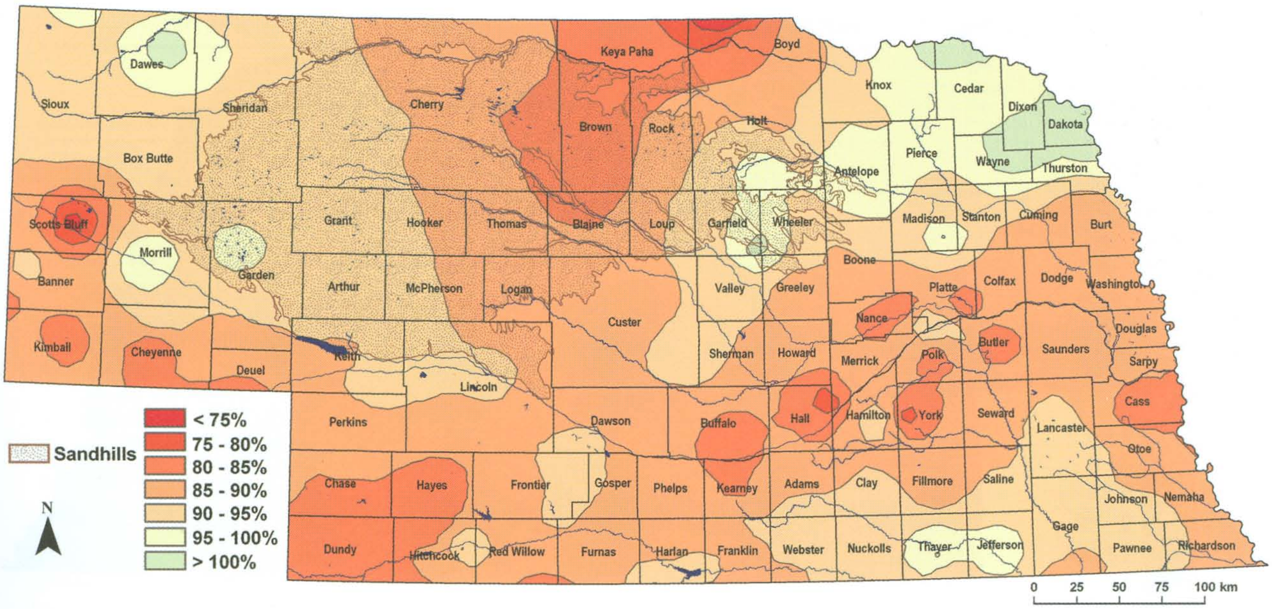

Figure 3. Area-weighted percentage of normal precipitation in Nebraska, January 2000 to January 2005.

recent available normal precipitation data are for the 30-year period 1971-2000 (NCDC 2005b).

Groundwater-level measurements collected during the spring of 2000 and spring of 2005 at 4,164 observation wells were used in this study. Possible bias in the data may result from differences in observation well characteristics. Observation wells in one area, for example, may be screened in different aquifers. Therefore, observation wells in an area may not respond equally to hydrologic stresses caused by drought or those caused by irrigation well pumping. The response of a local groundwater system to drought is dependent on many hydrogeologic factors, including depth to water, thickness and geologic composition of the unsaturated zone, and hydraulic characteristics of the aquifer. Net five-year gains or losses were calculated by subtracting spring 2005 measurements from spring 2000 measurements.

RESULTS

During the recent drought period, precipitation was below normal for all of Nebraska except for the northeast and small areas in the panhandle and the southeast (Fig. 3). More than 90% of the state experienced below-normal precipitation from 2000 through 2004. Large areas in the southwestern panhandle, northern, southwestern, and east-central parts of the state experienced less than 80% of normal precipitation (Fig. 3). Two small areas in the western panhandle and extreme north-central parts of the state experienced less than 75% of normal precipitation (Fig. 3). The minimum reported rainfall amount in Nebraska was 72% of normal in Scotts Bluff County in the panhandle. The minimum reported rainfall amount in all 150 monitoring stations was 58% of normal at a weather station in South Dakota immediately adjacent to north-central Nebraska. The maximum reported rainfall amount in the 150 monitoring stations was 108% of normal in Dakota County in northeast Nebraska.

Normal precipitation increases over twofold from northwest (<400 mm) to southeast (~900 mm) across Nebraska. The 72% percent of normal precipitation received in Scotts Bluff County in western Nebraska during 2000-2005 is a deficit of more than 580 mm, which is equivalent to more than 1.5 years of normal precipitation. The five-year deficit in Cass County in eastern Nebraska was nearly 950 mm, or the equivalent of 1.1 years of normal precipitation.

With the exception of north-central Nebraska, the areas with the largest precipitation shortfalls were also in areas with low annual recharge rates to groundwater as a percentage of precipitation (Fig. 4). The resultant decreases in recharge in these regions can be estimated using the modeled recharge rates for these regions. The normal recharge rate near the Scottsbluff weather station in Scotts Bluff County in western Nebraska is about 6% of precipitation, or 25 mm/yr. The cumulative impact of the

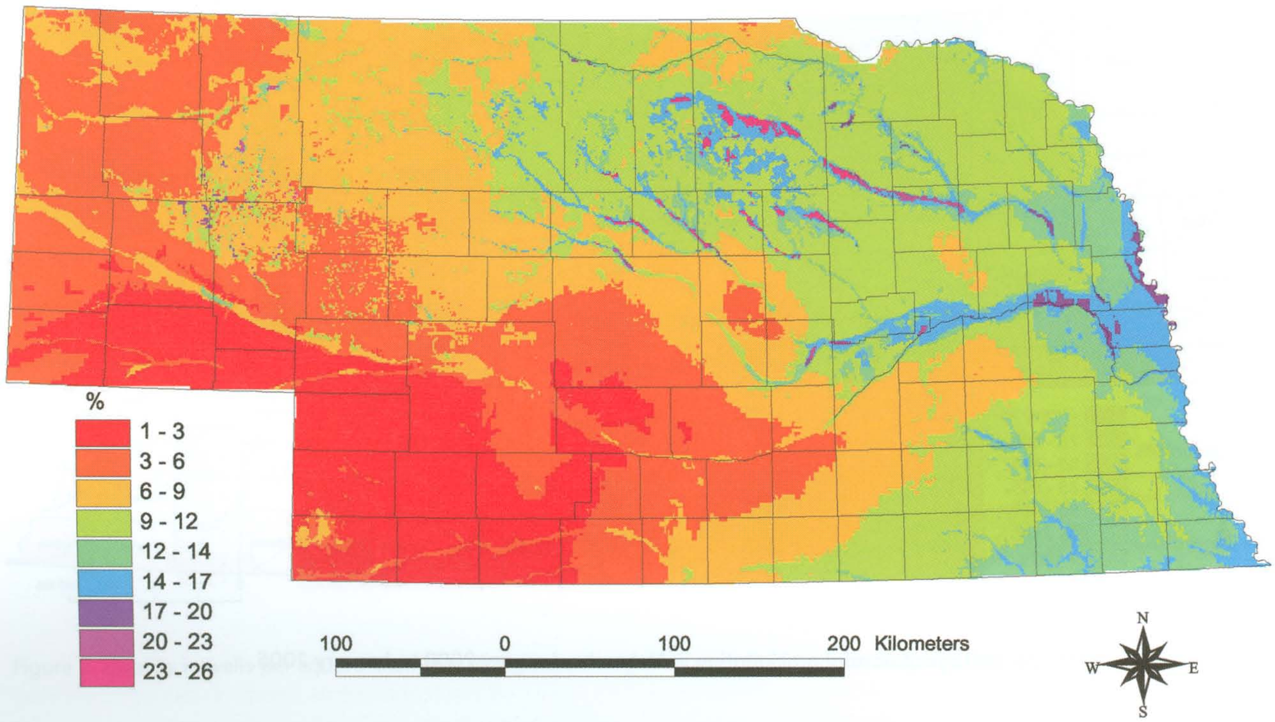

Figure 4. Estimated mean annual total recharge rates as percentage of precipitation in Nebraska (from Szilagyi et al. 2005).

drought in this region was a 38 mm decline in recharge (Table 1), or the equivalent of more than 1.5 years of normal recharge. The normal recharge rate near the Grand Island weather station in Hall County in south-central Nebraska is about 7 percent of precipitation, or 46 mm/yr. The cumulative impact of the drought in this region was a 54 mm decline in recharge, or the equivalent of nearly 1.2 years of normal recharge.

More than 75% of the state of Nebraska experienced groundwater-level declines of at least 0.3 m during the five-year period (Fig. 5). Large areas that experienced declines greater than 3 m include Box Butte, Cheyenne, and Sheridan counties in the panhandle, extreme southwestern Nebraska, Holt County in the north, and south-central Nebraska along the Platte River. Some areas in east-central Nebraska experienced declines of more than 9 m. The Sandhills experienced no declines or modest declines of less than 1.5 m. The only area with an increase (~1 m) in the local groundwater level was in Valley County. Unlined irrigation canals are most likely responsible for this rise.

The number of registered irrigation wells in Nebraska increased dramatically during the drought period. Between January 2000 and January 2006, more than 19,000 irrigation wells were registered in Nebraska (NDNR 2006). This is a 23% increase in the number of registered irrigation wells since the onset of the drought. The increase in registered irrigation wells probably did not result in a proportional increase in volume of groundwater withdrawals because the new irrigation systems are more efficient than older systems.

In addition to the drought, three recent regulatory developments are likely to have contributed to the sharp increase in irrigation well installation. Because these developments are very recent and their implications are far from fully realized, their effects cannot yet be quantified.

First, Nebraska, Colorado, Wyoming, and the U.S. Department of Interior (represented by U.S. Fish and Wildlife Service and U.S. Bureau of Reclamation) entered into the Platte River Cooperative Agreement in July 1997 in order to develop and implement a recovery implementation program (COHYST 2005). One highly controversial component of the agreement was that no new depletions to the Platte River or its tributary streams would be allowed. The Fish and Wildlife Service interpreted this component to potentially prohibit new depletions from groundwater pumping as well as depletions of surface water. In anticipation of possible future prohibition, some landowners in the Platte River basin may have installed new irrigation wells in the late 1990s and early 2000s.

TABLE 1
CHANGE IN RECHARGE NEAR NEBRASKA WEATHER STATIONS, 2000-2005

Station, County	Five-year percentage of normal precipitation	Normal five-year recharge (mm)	Estimated loss/ gain in recharge (mm)	Station, County	Five-year percentage of normal precipitation	Normal five-year recharge (mm)	Estimated loss/gain in recharge (mm)
Agate, Sioux	98	82	-2	Kearney, Buffalo	77	144	-33
Anselmo, Custer	79	191	-40	Kearney 4 NE, Buffalo	83	144	-25
Arthur, Arthur	92	119	-9	Kimball, Kimball	83	66	-11
Ashland, Saunders	86	490	-68	Kingsley Dam, Keith	89	214	-24
Auburn, Nemaha	84	575	-90	Lincoln, Lancaster	92	468	-35
Aurora, Hamilton	95	277	-14	Lodgepole, Cheyenne	87	70	-9
Barneston, Gage	89	572	-61	Loretto, Boone	89	371	-40
Beaver City, Furnas	90	226	-23	Lyman, Scotts Bluff	86	115	-16
Benkelman, Dundy	89	74	-8	Lynch, Boyd	88	322	-40
Blue Hill, Webster	96	346	-13	Lyons, Burt	86	476	-67
Bradshaw, York	77	270	-61	Madison, Madison	101	311	2
Bridgeport, Morrill	102	125	2	Madrid, Perkins	89	52	-6
Broken Bow, Custer	88	132	-16	Mason City, Custer	97	185	-5
Butte, Boyd	82	238	-43	McCook, Frontier	87	51	-7
Canaday, Gosper	85	85	-13	Medicine Creek Dam, Frontier	91	55	-5
Central City, Merrick	93	413	-28	Miller, Buffalo	87	107	-14
Chadron, Dawes	103	106	4	Minden, Kearney	84	145	-24
Chambers, Holt	98	398	-9	Neligh, Antelope	101	637	9
Clay Center, Clay	91	262	-24	Newcastle, Dixon	98	446	-8
Columbus, Platte	81	543	-105	Norfolk, Madison	90	609	-59
Creighton, Knox	94	402	-22	North Platte, Lincoln	91	150	-13
Crescent Lake, Garden	98	159	-3	Oakdale, Antelope	97	393	-14
Culbertson, Hitchcock	96	82	-3	Omaha-Eppley, Douglas	92	537	-43
Dalton, Cheyenne	95	49	-2	Omaha-Valley, Douglas	93	595	-41
David City, Butler	81	344	-67	O'Neill, Holt	89	655	-74
Dodge, Dodge	84	456	-75	Ord, Valley	93	278	-18
Deweese, Nuckolls	99	339	-4	Osceola, Polk	82	384	-71
Ellsworth, Sheridan	91	115	-10	Oshkosh, Garden	90	152	-15
Elsmere, Brown	80	385	-78	Osmond, Pierce	97	378	-10
Ericson, Garfield	103	286	7	Palisade, Hitchcock	74	83	-21
Eustis, Frontier	98	83	-2	Parks, Dundy	83	49	-8
Fairbury, Jefferson	100	472	-1	Paxton, Keith	102	70	1
Fremont, Dodge	87	662	-87	Randolph, Pierce	93	332	-25
Friend, Saline	90	406	-42	Red Cloud, Webster	90	318	-32
Fullerton, Nance	82	479	-86	Schuyler, Colfax	89	450	-49
Geneva, Filmore	84	359	-59	Scottsbluff, Scotts Bluff	72	135	-38
Genoa, Nance	82	459	-84	Seward, Seward	90	320	-33
Gordon, Sheridan	95	140	-7	Sidney, Cheyenne	81	72	-14
Gothenburg, Dawson	87	127	-17	Stapleton, Logan	88	162	-19
Grand Island, Hall	77	230	-54	St. Paul, Howard	87	413	-54
Greeley, Greeley	86	314	-45	Superior, Nuckolls	90	428	-41
Harlan County Dam, Harlan	92	220	-18	Syracuse, Otoe	90	448	-46
Harrisburg Banner	95	85	-5	Table Rock, Pawnee	97	546	-16
Harrison, Sioux	87	91	-12	Taylor, Loup	90	270	-26
Hartington, Cedar	97	367	-12	Trenton, Hitchcock	87	81	-11
Hastings, Adams	84	213	-34	Upland, Franklin	91	196	-18
Hayes Center, Hayes	80	55	-11	Valentine, Cherry	86	198	-27
Hebron, Thayer	101	434	6	Wakefield, Dixon	104	437	20
Hemingford, Box Butte	91	98	-9	Wallace, Lincoln	86	48	-7
Hickman, Lancaster	95	427	-20	Wayne, Wayne	102	351	7
Holdrege, Phelps	85	198	-29	Weeping, Water Cass	78	513	-114
Homer, Dakota	108	482	39	West Point, Cuming	90	645	-65
Hubbell, Thayer	92	413	-33	York, York	82	268	-47

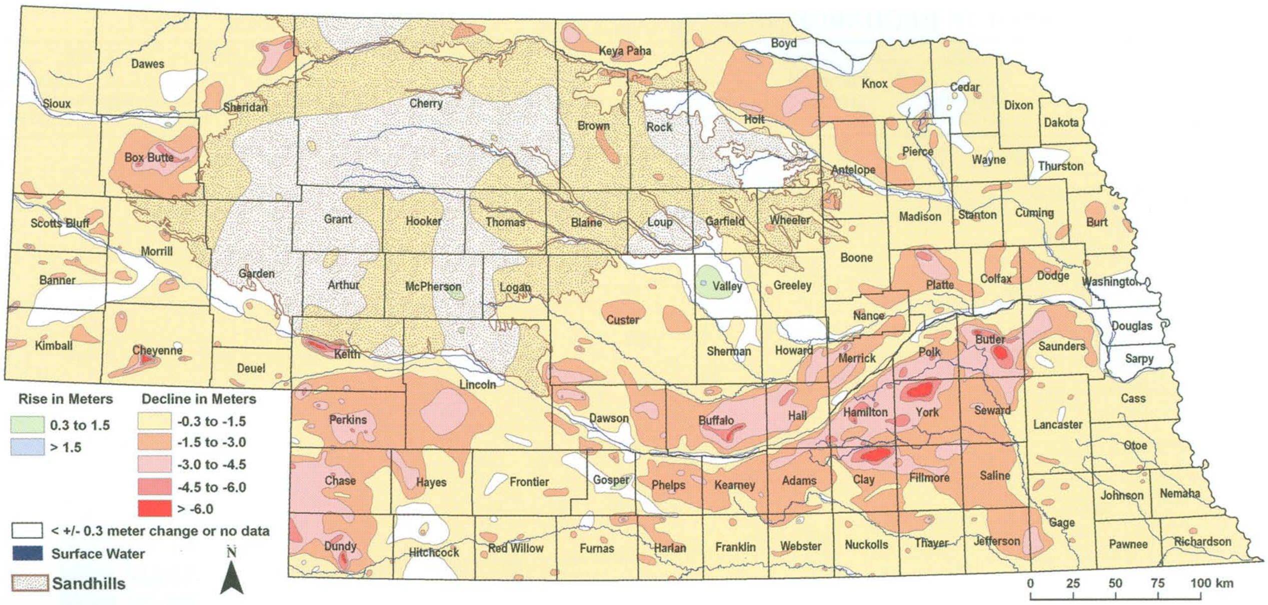

Figure 5. Groundwater-level changes in Nebraska, spring 2000 to spring 2005.

A second additional factor that may have contributed to the increase in irrigation well installation is the Republican River Compact litigation settlement in December 2002 (NDNR 2003). As in the Platte Valley, some landowners in the Republican Basin may have preemptively installed new wells in anticipation of future restrictions.

A third factor is passage of Nebraska Legislative Bill (LB) 962. This law instructed the Nebraska Department of Natural Resources to identify fully or overappropriated basins in the state and to limit groundwater withdrawals in these basins (NDNR 2005). Some landowners have installed new wells in anticipation of a fully appropriated designation. LB 962 was from its inception largely a response to concern about the current drought.

Irrigation wells in Nebraska are not evenly distributed (Fig. 2). Rather, they are located in areas that have adequate groundwater resources and soils and topography conducive to intense cropping systems. The most severe groundwater-level declines during 2000-2005 were in the most intensely groundwater-irrigated regions of the state. Conversely, areas with little or no change in groundwater levels during the five-year period have little groundwater irrigation.

In some instances, the current drought has exacerbated preexisting groundwater-level problems. Groundwater levels in parts of the panhandle and southwest had already declined more than 15 m prior to 2000. These regions experienced additional declines exceeding 3 m during the current drought period.

Large areas in south-central and southeastern Nebraska also experienced groundwater-level declines exceeding 3 m during the five-year period. In the 1970s and 1980s, these areas experienced large declines from predevelopment groundwater levels, but groundwater levels in parts of these areas rose dramatically during the 1990s. The 10-year period from 1990 through 1999 was the wettest decade on record in eastern Nebraska (NCDC 2005b). The current drought, however, has negated the substantial recovery of groundwater levels in portions of this area.

SUMMARY AND CONCLUSIONS

Much of Nebraska has received less than 85% of normal precipitation during the recent drought. The range of precipitation reported at weather stations in Nebraska during the drought period was 72% to 108% of normal. A sharp increase in irrigation well installation coincides with the below normal precipitation, indicating a wholesale attempt to offset the agroeconomic effects of the drought.

Groundwater levels have declined across much of Nebraska during the recent drought. Declines were most severe in groundwater-irrigated regions. Areas with little or no groundwater irrigation, however, experienced only modest declines. Locations in western Nebraska with extensive groundwater irrigation development and low groundwater recharge rates experienced dramatic groundwater-level declines prior to the current drought. Recovery from the drought will be particularly difficult in these areas.

In general, the most vulnerable areas to agricultural drought are nonirrigated cropland and rangeland (Wilhelmi and Wilhite 2002). However, the results of our study indicate that in Nebraska the most vulnerable areas to hydrological drought, particularly with respect to impact on groundwater, are agricultural areas with high concentrations of irrigation wells. The identification of vulnerable areas is an essential step in drought response in the state and should promote mitigation-oriented drought management. Application of the lesson learned from the recent drought can only improve groundwater management in Nebraska.

The current drought in Nebraska is minor compared to those determined from the recent geologic record (e.g., Woodhouse et al. 2002; Mason et al. 2004). Some climate-change models predict sharp declines in precipitation within this century in portions of the Great Plains (e.g., Gregory et al. 1997; Rosenberg 1999; Thomson et al. 2005). Others predict that, while winter precipitation may increase in some parts of the United States, precipitation during the summer growing season may decrease in this century (e.g., Wuebbles and Hayhoe 2004). Longer and more intense droughts could be catastrophic for the entire United States, because the Great Plains produces nearly one-quarter of U.S. agricultural crops and livestock. More importantly, however, short-term decreases in rainfall in the Great Plains can clearly produce disproportionately large impacts in areas already susceptible to groundwater-level declines. Some parts of the Great Plains have experienced dramatic groundwater-level declines and can no longer support groundwater irrigation (e.g., McGuire et al. 2003). Schloss and Buddemeier (2000) estimate the usable life of groundwater supplies in much of western Kansas to be less than 25 years.

Large parts of the Great Plains have experienced population declines and declining viability for decades, even though the nation's dependence on agricultural products from the region remains high. In a study of water use and population redistribution in the High Plains aquifer region of western Kansas, White (1994, 42) found that "population change is significantly associated with groundwater exploitation," and moreover, "proximity to groundwater use emerges as a major determinate of population change, particularly among places with more than 500 inhabitants."

The current drought and subsequent increase in irrigation well installations have further dramatized the importance of groundwater in Nebraska and the surrounding Great Plains. Furthermore, Lamphear (2005) found "the economic impact of irrigation in Nebraska in 2003 was $4.5 billion" and "the total economic impact from irrigation accounts for roughly 17% of total agribusiness activity in Nebraska." Gilson et al. (2001) conservatively estimated 9% of the economic activity of western Kansas is attributable to irrigated farming. According to the Western Kansas Irrigation Research Project at Kansas State University (1998), the number of irrigated acres in western Kansas is expected to decline between 40% and 85% by 2020 due to declines in the water table and higher energy costs for pumping.

The current drought has impacted a large portion of the central and northern Great Plains, which depends on irrigation for supplemental crop water needs. Some parts of the central and northern Great Plains may be approaching an environmental and socioeconomic threshold beyond which a return to earlier conditions of adequate groundwater supplies for irrigation may not be possible. Indeed, some portions of southwestern Kansas have already reverted to dryland cropping practices because of declining groundwater levels. Therefore, an intelligent and more sustainable long-term strategy for water use and natural hazards risk reduction (e.g., Anderson 1994; Mehta 1997; Mileti 1999; Mileti et al. 1995) is the best hope for the future of civilization in the Great Plains.

ACKNOWLEDGMENTS

The authors would like to thank two anonymous reviewers, as well as James Swinehart and Marvin Carlson, for their constructive criticisms of this manuscript. We are grateful to Les Howard and Dee Ebbeka for their help in creating some of the figures. We also want to thank the National Drought Mitigation Center and Jozsef Szilagyi for permission to reproduce their maps.

REFERENCES

Alverson, K., R.S. Bradley, and T.F. Pedersen, eds. 2003. *Paleoclimate, Global Change, and the Future.* Springer Verlag, Berlin, Germany.

Anderson, M.B. 1994. Vulnerability to disaster and sustainable development: A general framework for assessing vulnerability. In *Disaster Prevention for Sustainable Development: Economic and Policy Issues*, ed. M. Munasinghe and C. Clarke. Report from the Yokohama World Conference on Natural Disaster Reduction, May 23-27, 1994. World Bank, Washington, DC.

Butterworth, J.A., R.E. Schulze, L.P. Simmonds, P. Moriarty, and F. Mugabe. 1999. Long-term groundwater level fluctuations due to variation in rainfall. *Hydrology and Earth System Sciences* 3:353-61.

COHYST. 2005. Platte River Cooperative Hydrology Study (COHYST). http://cohyst.dnr.state.ne.us/ (accessed September 30, 2005).

Federal Emergency Management Agency (FEMA). 1995. *National Mitigation Strategy: Partnerships for Building Safer Communities.* FEMA, Washington, DC.

Gilson, P., J.A. Aistrup, J. Heinrichs, and B. Zollinger. 2001. *The Value of the Ogallala Aquifer Water in Southwest Kansas.* Docking Institute of Public Affairs, Fort Hays State University, Hays, KS.

Gregory, J.M., J.F.B. Mitchell, and A.J. Brady. 1997. Summer drought in northern midlatitudes in a time-dependent CO_2 climate experiment. *Journal of Climate* 10:662-86.

Guyette, R.P., M.C. Stambaugh, and D.C. Dey. 2004. Ancient oak climate proxies from the agricultural heartland. *EOS* 85:483.

Hayes, M.J., M.D. Svoboda, C.L. Knutson, and D.A. Wilhite. 2004. Estimating the economic impacts of drought. Paper presented at the joint conference of the 15th Symposium on Global Change and Climate Variations and the 14th Conference on Applied Climatology, Seattle, WA.

Heim, R.R. Jr., 2002. A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society* 83:1149-65.

Hewitt, K. 1997. *Regions at Risk: A Geographical Introduction to Disasters.* Addison Wesley Longman, London, UK.

Hutson, S.S., N.L. Barber, J.F. Kenny, K.S. Linsey, D.S. Lumia, and M.A. Maupin. 2004. *Estimated Use of Water in the United States, 2000.* U.S. Geological Survey Circular 1268. U.S. Geological Survey (USGS), Reston, VA.

Karl, T.R. 1983. Some spatial characteristics of drought duration in the United States. *Journal of Climate and Applied Meteorology* 22:1356-66.

Karl, T.R., F. Quilan, and D.D. Ezell. 1987. Drought termination and amelioration: Its climatological probability. *Journal of Climate and Applied Meteorology* 26:1198-1209.

Knapp, P.A., P.T. Soulé, and H.D. Grissino-Mayer. 2004. Occurrence of sustained droughts in the interior Pacific Northwest (A.D. 1733-1980) inferred from tree-ring data. *Journal of Climate* 17:14-50.

Lamphear, C. 2005. Economic importance of irrigated agriculture. *Nebraska Water Resources Association* (Newsletter), Fall, 1.

Loope, D.B., and J.B. Swinehart. 2000. Thinking like a dune field: Geologic history in the Nebraska Sand Hills. *Great Plains Research* 10:5-35.

Mason, J.A., J.B. Swinehart, R.J. Goble, and D.B. Loope. 2004. Late Holocene dune activity linked to hydrological drought, Nebraska Sand Hills, USA. *Holocene* 14:209-17.

McGuire, V.L. 2004. *Water-Level Changes in the High Plains Aquifer, Predevelopment to 2003 and 2002 to 2003.* U.S. Geological Survey Fact Sheet 2004-3097. U.S. Geological Survey (USGS), Reston, VA.

McGuire, V.L., M.R. Johnson, R.L. Schieffer, J.S. Stanton, S.K. Sebree, and I.M. Verstraeten. 2003. *Water in Storage and Approaches to Ground-Water Management, High Plains Aquifer, 2000.* U.S. Geological Survey Circular 1243. U.S. Geological Survey (USGS), Reston, VA.

Mehta, M.D. 1997. Risk assessment and sustainable development: towards a concept of sustainable risk. *Risk: Health, Safety, and Environment* 8:137-54.

Mileti, D.S. 1999. *Disasters by Design.* Joseph Henry Press, Washington, DC.

Mileti, D.S., J.D. Darlington, E. Passerini, B.C. Forrest, and M.F. Myers. 1995. Toward an integration of natural hazards and sustainability. *The Environmental Professional* 17:117-26.

Montana Department of Natural Resources and Conservation (MDNRC). 2006. DNRC Water Right Query System. http://nris.mt.gov/dnrc/waterrights/default.aspx (accessed January 5, 2006).

National Climatic Data Center (NCDC). 2003. Climate of 2002: Annual review, U.S. drought. http://lwf.ncdc.noaa.gov/oa/climate/research/2002/ann/drought-summary.html (accessed April 5, 2005).

National Climatic Data Center (NCDC). 2005a. Billion Dollar US Weather Disasters, 1980-2004. http://www.ncdc.noaa.gov/oa/reports/billionz.html (accessed April 5, 2005).

National Climatic Data Center (NCDC). 2005b. Nebraska Climate Summary, July 2005. http://lwf.ncdc.noaa.gov/oa/climate/research/cag3/ne.html (accessed August 22, 2005).

Nebraska Department of Natural Resources (NDNR). 2003. Summary of Republican River Compact litigation settlement. http://www.dnr.state.ne.us/Republican/RepRiverLitigation_Lg.pdf (accessed September 30, 2005).

Nebraska Department of Natural Resources (NDNR). 2005. What is the meaning of LB962's fully appropriated basin designation? http://www.dnr.state.ne.us/LB962/LB962Implementation.html (accessed September 30, 2005)

Nebraska Department of Natural Resources (NDNR). 2006. Registered groundwater wells data retrieval. http://dnrdata.dnr.state.ne.us/wellssql/ (accessed January 6, 2006).

National Drought Mitigation Center (NDMC). 2005. U.S. Drought Monitor. Prepared by the National Drought Mitigation Center, U.S. Department of Agriculture, and National Oceanic and Atmospheric Administration. Available at http://drought.unl.edu/dm/.

Neilson, M.J., and D.N. Bearce. 1998. Seasonal Variations in Water Table Elevations in the Surficial Aquifer, Birmingham Valley. *Journal of the Alabama Academy of Science* 69:175-82.

Nicholson, B.J., and J.B. Swinehart. 2005. Evidence of Holocene climate change in a Nebraska Sandhills wetland. *Great Plains Research* 15:45-67.

Peterson, J.M., T.L. Marsh, and J.R. Williams. 2003. Conserving the Ogallala Aquifer: Efficiency, equity, and moral motives. *Choices Magazine* 18 (1st quarter): 15-18.

Pielke, R.A. Sr., N. Doesken, O. Bliss, T. Green, C. Chaffin, J.D. Salas, C.A. Woodhouse, J.J. Lukas, and K. Wolter. 2005. Drought 2002 in Colorado: An unprecedented drought or a routine drought? *Pure and Applied Geophysics* 162:1455-79.

Polsky, C. 2004. Putting space and time in ricardian climate change impact studies: Agriculture in the U.S. Great Plains, 1969-1992. *Annals of the Association of American Geographers* 94:549-64.

Rosenberg, N.J., D.J. Epstein, D. Wang, L. Vail, R. Srinivasan, and J.G. Arnold. 1999. Possible impacts of global warming on the hydrology of the Ogallala Aquifer region. *Climatic Change* 42:677-92.

Schloss, J.A., and R.W. Buddemeier. 2000. Estimated usable lifetime. In *An Atlas of the Kansas High Plains Aquifer*, ed. J.A. Schloss, R.W. Buddemier, and B.B. Wilson. Educational Series 14. Kansas Geological Survey, Lawrence, KS.

Scholle, P., and M.L. Allison. 2002. Science needs for managing the High Plains aquifer. Testimony presented to the Senate Committee on Energy and Natural Resources, Subcommittee on Water and Power, Hearing on Senate Bill 2773, High Plains Aquifer Hydrogeologic Characterization, Mapping, Modeling, and Monitoring Act. http://www.kgs.ukans.edu/Hydro/HPAC/Testimony/scholle.html (accessed March 29, 2005).

Soulé, P.T. 1992. Spatial patterns of drought frequency and duration in the contiguous USA based on multiple drought event definitions. *International Journal of Climatology* 12:11-24.

Soulé, P.T. 1993. Hydrological drought in the contiguous United States, 1900-1989: Spatial patterns and multiple comparison of means. *Geophysical Research Letters* 20:2367-70.

Szilagyi, J., F.E. Harvey, and J.F. Ayers. 2005. Regional estimation of total recharge to ground water in Nebraska. *Ground Water* 43:63-69.

Taylor, C.J., and W.M. Alley. 2001. *Ground-Water-Level Monitoring and the Importance of Long-Term Water-Level Data*. U.S. Geological Survey Circular. U.S. Geological Survey (USGS), Reston, VA.

Thomson, A.M., R.A. Brown, N.J. Rosenberg, R. Srinivasan, and R.C. Izaurralde. 2005. Climate change impacts for the conterminous USA: An integrated assessment, pt. 4: Water resources. *Climatic Change* 69:67-88.

U.S. Public Interest Research Group (US PIRG), Education Fund. 2003. The costs of inaction: Delaying action on global warming costs consumers and the environment. http://uspirg.org/reports/costsofinaction10_03.pdf (accessed April 7, 2005).

Vörösmarty, C.J., and D. Sahagian. 2000. Anthropogenic disturbance of the terrestrial water cycle. *Bioscience* 50:753-65.

Walsh, J.E., M.B. Richman, and D.W. Allen. 1982. Spatial coherence of monthly precipitation in the United States. *Monthly Weather Review* 110:272-86.

Wendland, W.M. 2001. Temporal responses of surface-water and ground-water to precipitation in Illinois. *Journal of the American Water Resources Association* 37:685-93.

Western Kansas Irrigation Research Project. 1998. Brochure, Kansas State University Research and Extension, Manhattan, KS.

White, S.E. 1994. Ogallala oases: Water use, population, redistribution, and policy implications in the High Plains of western Kansas, 1980-1999. *Annals of the Association of American Geographers* 84:29-45.

Wilhelmi, O.V., and D.A. Wilhite. 2002. Assessing vulnerability to agricultural drought: A Nebraska case study. *Natural Hazards* 25:37-58.

Wilhite, D.A. 2005. Drought: Understanding the hazard and reducing societal vulnerability. Paper presented at Second Annual Water Law, Policy and Science Conference, April 7-8, Lincoln, NE.

Wilhite, D.A. 2000. Drought as a natural hazard: Concepts and definitions. In *Drought: A Global Assessment*, ed. D.A. Wilhite. Natural Hazards Disasters Series. Routledge, Oxford, UK.

Woodhouse, C.A., J.J. Lukas, and P.M. Brown. 2002. Drought in the Western Great Plains, 1845-56: Impacts and implications. *Bulletin of the American Meteorological Society* 83:1485-93.

Woodhouse, C.A., and J.T. Overpeck. 1998. 2,000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society* 79:2693-2714.

Worster, D. 1979. *Dust Bowl: The Southern Plains in the 1930s.* Oxford University Press, New York, NY.

Wuebbles, D.J., and K. Hayhoe. 2004. Climate change projections for the United States Midwest. *Mitigation and Adaptation Strategies for Global Change* 9:335-63.

Wyoming State Engineers Office (WSEO). 2006. Water rights database. http://seo.state.wy.us/wrdb/index.aspx (accessed January 11, 2006).

Manuscript received for review, September 2005; accepted for publication, February 2006.