High Plains Aquifer Hydrologic Observatory: Prospectus

Submitted to the

Consortium of Universities for the Advancement of Hydrologic Sciences, Inc.

On behalf of the

Consortium for Global Research on Water-Based Economies (GRoWE)

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1. Spatial Extent of Hydrologic Observatory

The High Plains Aquifer encompasses 174,000 square miles in eight states (figure 1), and provides the primary source of potable water to the region. The hydrologic cycle exhibits great diversity across this geological basin, with significant expanses experiencing sustained declines in groundwater elevation (e.g., portions of the southern and central basins in Kansas, New Mexico, Oklahoma, and Texas) while other areas are experiencing rises (e.g., portions of the northern basin in central Nebraska).

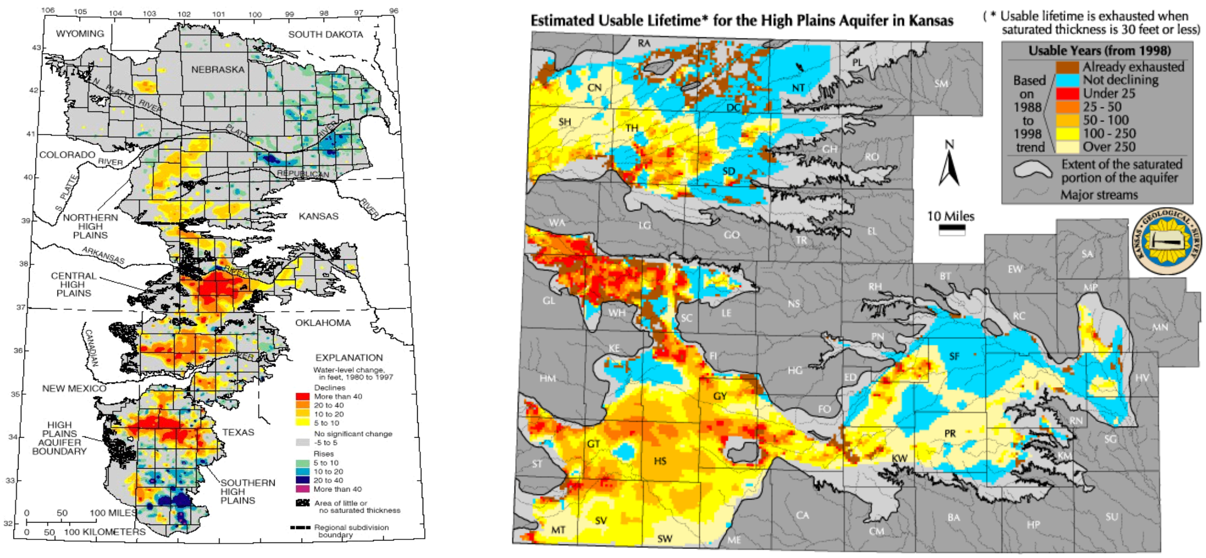

Figure 1. Groundwater declines in the High Plains Aquifer from 1980 to 1997 (McGwire and Fischer, 1999), and estimated usable lifetime in Kansas (Hecox et al. 2002).

The regions of intensive groundwater decline in the High Plains Aquifer reflect global water-use practices; “Presently, irrigation accounts for 70% of all water withdrawals … [*increasing*] by 14% in the next 30 years.” (UNESCO, 2003). In fact, the High Plains Aquifer was identified by National Geographic (Montaigne, 2002) as a “critical area” for “annual renewable water” in the United States of America, and exemplifies water issues facing other regions of the world (e.g., in Africa, Asia, the Middle East and South America). Thus, observing and understanding the hydrology of the High Plains Aquifer would provide the foundation for understanding the hydrology of likewise endangered systems throughout the world.

The atmosphere/surface/aquifer interactions within the hydrologic cycle are illustrated in figure 2. Recharge is that portion of precipitation, which is not lost as evaporation, run off or root uptake, and eventually migrates downward to saturated groundwater regions. Recharge and evapotranspiration (ET) processes vary across the High Plains Aquifer and contain intrinsically coupled system interactions. Recharge to aquifers is utilized in land-use practices that withdraw groundwater (and surface water where available in riparian zones) to supplement plant water requirements not met through precipitation. Supplemental irrigation and introduction of exogenous plant species, in turn, impacts recharge rates. Thus, observations of atmosphere/surface/aquifer interactions form the cornerstone for system-wide hydrologic understanding within the High Plains Aquifer.

A. Scientific Rationale for Design

The proposed High Plains Aquifer Hydrologic Observatory would promote significant scientific advancement in hydrology related to:

1. *Recharge and evapotranspiration*
2. *Surface water-groundwater exchange in dynamic riparian corridors*
3. *Ecological role of vegetation in the hydrologic cycle*
4. *Human systems and the hydrologic cycle*
5. *Multi-scale monitoring, modeling & analysis*
6. *Climate change studies*
7. *Utilization of remote sensing technology*

The need for scientific observation in each area of advancement is briefly described.

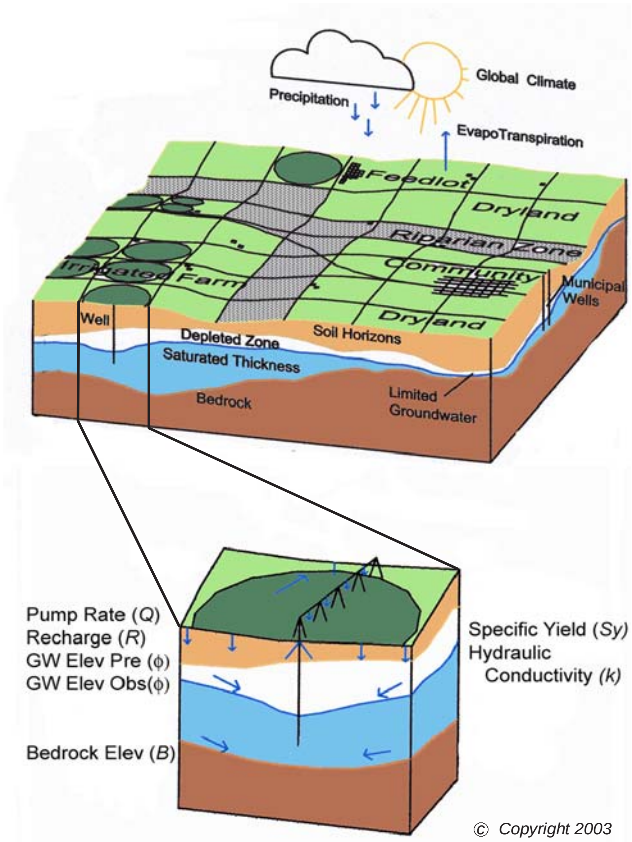

Figure 2. Atmosphere / Surface / Aquifer hydrologic interactions contain complicated forcing and feedback mechanisms that vary spatially and temporally, and are controlled by a multiplicity of natural and social components within the system (source: Steward and Bernard, 2004).

Advancement 1. Recharge and ET: Recharge and ET are areal processes, which vary over space and time, and must currently be inferred/extrapolated from other data with, at best, limited groundtruthing using existing data sources.

Advancement 2. Surface Water-Groundwater Exchange in Dynamic Riparian Corridors: Riparian zones provide the most direct link between the atmosphere and groundwater, providing sites of enhanced recharge as well as discharge to the environment through baseflow and neighboring phreatophytes, and providing an important source for aquifer salinization and mineralization.

Advancement 3. Ecological Role of Vegetation in the Hydrologic Cycle: Native and introduced vegetation have water use requirements that must be met through precipitation (global climate) or irrigation (groundwater withdrawal). The type of vegetation also relates to rooting characteristics and response to rainfall events, impacting recharge and carbon sequestration rates, and phytoremediation capabilities.

Advancement 4. Human Systems and the Hydrologic Cycle: Water resources cannot be studied solely from a hydrological perspective but must incorporate social components that influence and derive from complex interactions of natural and human systems. The intensive use of groundwater in recent decades that exceeds recharge rates has occurred in the context of a local economy developed around irrigated agriculture. A declining stock of groundwater is, however, forcing transition to sustainable water use that matches recharge rates. This, in turn, will significantly impact economies, human populations, plant communities and the landscape.

Advancement 5. Multi-Scale Monitoring, Modeling & Analysis: Data related to the hydrologic cycle are collected from relatively small field scales to continental scales using satellite imagery. Interrelated sociodemographic and economic data are typically collected at intermediate scales. Developing multi-scale data sets, modeling tools and approaches to integrate data to common scales addressing an area the size of the High Plains Aquifer would produce significant advances in our understanding of scaling issues.

Advancement 6. Climate Change Studies: Hydrologic observations over a region with significant climatic variation would provide data to estimate the impacts of alternative possible climate changes on the landscape.

Advancement 7. Utilization of Remote Sensing Technology: Hydrologic observations would provide a test bed for validation and verification of remote sensing technologies.

Scientific advancements are related to the five top priority scientific topics identified by CUAHSI (Hooper et al. 2004):

- Sustainability of water resources: ET and recharge rates could be correlated with the sustainability of existing and proposed land-use practices, scaling results from local field scale to the region.
- Hydrologic and ecosystem interactions: The role of playa lakes and ephemeral streams in recharge would be identified, as well as the role of native and exogenous plants and phreatophytes in these ecosystems.
- Hydrologic extremes: The impacts of global climate change across a region with diversity in soil type, hydrogeology, land-use practices and management strategies would be examined.
- Linking hydrologic and biogeochemical cycles: Carbon sequestration rates and induced groundwater salinization through riparian zones would be characterized.
- Fate and transport of chemical and biological contaminants: The relationship between recharge and ET in non-point source pollution and contaminant transport would be observed for a variety of land uses through riparian and groundwater zones.

Likewise, each of the areas of scientific advancement relates to the cross-cutting themes (Hooper et al. 2004) of 1) Forcing, feedbacks and coupling, 2) Scaling, and 3) Predictions and the limits of predictability.

B. Site Characteristics

A spectrum of site characteristics exists across the High Plains Aquifer with significant variations in:

- Water availability
- Aquifer characteristics
- Climatic conditions
- Soil type
- Land-use practices
- Water policy and regulation
- Sociodemographic characteristics (as they relate to water views and practices)
- Data quality and type.

Although most of the High Plains Aquifer underlies unglaciated plains, considerable variation exists in both water use and precipitation across the region. Estimates of recharge rates range from 0.024 inches per year in parts of Texas to 6 inches per year in the sand dune areas of Kansas and Nebraska. Conversely, water use in parts of the aquifer often exceeds 20 inches per year and significant areas experience sustained declines of 3 feet per year or more (figure 1). There is considerable variation in saturated thickness, and depth to the water table varies from a few feet to hundreds of feet. The region also contains numerous playa lakes and ephemeral rivers that may provide focused recharge.

The range of water fluxes in the High Plains Aquifer region is illustrated in figure 3, with numbers indicating the potential evapotranspiration (PET) in inches per year. The average precipitation varies from 12 to 35 inches per year, with the orange region depicting precipitation over 20 inches per year. As indicated, PET is extremely variable being largely controlled by differences in humidity, temperature, elevation and wind speed. The actual ET values are considerably less than the PET values (although still variable) and are strongly dependent on specific land uses. For example, actual ET for irrigated corn is approximately 30 inches per year, while it is close to 100% of annual precipitation for dryland wheat.

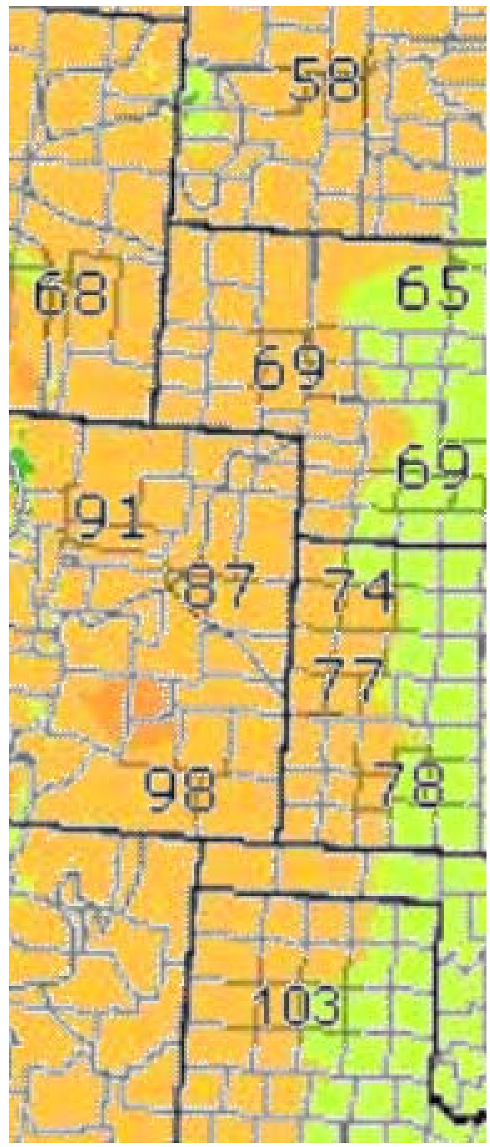

Figure 3. Potential ET values were determined by the Penman method using data from the Kansas State University Weather Data Library (http://www.oznet.ksu.edu/wdl/).

The High Plains region is a prime location for studying human decisions in response to climate change, for climate change has been an enduring characteristic of the region. The climate of the High Plains is semiarid or steppe, characterized by a continental temperature regime with mean monthly temperatures ranging from 5 to 22 C. Interannual variability in precipitation is substantial, ranging from droughts to flood conditions, where drought conditions occur frequently and may last several years (IPCC, 2001). The "dust-bowl" era is the most well known occurrence of drought in the region, but droughts also occurred in the 1890s, 1910s, 1950s, 1980s, the early 2000s to present. Extreme weather events, such as thunderstorms, tornadoes and high winds, occur frequently in the region. Moreover, spatial variability exists in climatological conditions, as exhibited by the above discussions of precipitation and ET. The severity of drought conditions and extreme weather events also vary across the region. This spatial variability in climatological conditions provides researchers with different scenarios of climate change that can be used as cases for climate change forecasting.

The High Plains aquifer has sustained economic development in the region for the past half century, but the result is that the regional economy is stunningly water-dependent (Leatherman, Cader and Bloomquist, 2003). Irrigated crop production accounts for the largest share of groundwater withdrawals from the aquifer. The resulting supply of grains and forages in the region has attracted a large number of livestock feeding operations over the past several decades, and regional meat processing facilities have also migrated to the region to take advantage favorable conditions for production of cattle and hogs. In fact, the region now accounts for over 84% of all cattle fed to market in the United States (NASS, 1991). The fear is that diminished groundwater supplies would severely reduce regional crop production, which would in turn reduce the economic activity in the livestock and meat industries. Indeed, many small communities have already suffered from the abandonment of irrigated agriculture. White (1992) found that population changes in the High Plains region were correlated with the amount of water available; communities surrounded by irrigators with small or declining amounts of water lost population between 1980 and 1990.

2. Existing Data Infrastructure

Hydrogeological data related to the High Plains Aquifer exist in GIS format and can be obtained from a variety of sources (e.g., see table 1). Comprehensive data related to aquifer characteristics are available from the USGS (water.usgs.gov). Hydrologic data for each of the eight states overlying the High Plains Aquifer are available from respective Federal Geographic Data Committee (FGDC) state data clearinghouses. The type and resolution of these data and the available metadata vary considerably, reflecting the needs of individual states' water policy and regulations. Interoperability of data from these different sources severely limits attempts to comprehensively study the High Plains Aquifer.

Table 1 Existing, relevant hydrologic datasets for the High Plains Aquifer

Data Set	Data Source	Hydrologic Information
Census of Agriculture	USDA	Farm and ranch irrigation survey
DEM	USGS	Digital Elevation Model
DOQQ	NSDI	Digital Orthophoto Quarter Quadrangles (land use)
DRG	USGS	Topographic maps
EDS	USGS	Surface water gauging stations
GAP	USGS	Land cover
Green Reports	KBS/KARS	Plant health and potential ET
High Plains Aquifer	USGS	Hydrogeologic parameters (e.g., recharge, groundwater elevation)
High Plains Climate	HPRCC	Automated Weather Data Network
HPGW	NAWQA/USGS	Groundwater resources, water quality assessment
NASS	USDA	National Agricultural Statistics
NCDC	NOAA	Temperature, precipitation
SSURGO	NRCS	Soil survey
STATSGO	USDA/SCS	Soil survey
SWIMS	KDHE	Surface Water Information Management System
TIGER	U.S. Census Bureau	Demographics
WIMAS	DWR/KGS	Water use information for all points of diversion
WIZARD	KGS	Groundwater elevation at wells
WWC5	KDHE	Drilling well logs

Hydrologic systems also contain a variety of natural and social processes that have traditionally been examined from individual disciplinary viewpoints, each with a self-consistent scientific method of discovery and system perspective. Data sets are disjointed across disciplines, reflecting the paradigms of individual disciplines. Providing a Hydrologic Observatory that successfully addresses these integrated components of proposed Advancements 1-7 requires new paradigms of scientific investigation.

The Consortium for Global Research on Water-Based Economies (GRoWE) is a collaborative team with expertise in natural (hydrology, geology, plant dynamics, climatology) and social systems (economics, demographics, ecological planning). Our common vision is:

> *To help citizens, planning agencies and policy makers understand the technical aspects of water resources management and the economic, social and natural system impacts of different management strategies*.

This vision is consistent with and complimentary to the High Plains Aquifer Coalition, a state-federal partnership to better understand the hydrogeology of water resources issues in the High Plains region. It is expected that the High Plains Aquifer Coalition would have a central role in this endeavor.

The collaborative data assembly that is already underway has the aim of integrating the currently disjointed data sets. Specifically, relevant hydrological data are being integrated with data on soil characteristics, topography, climatic conditions, land cover, agricultural land-use practices, local economies, sociodemographic characteristics and water policies for geographic areas in the High Plains region. Although these data are all available at a national scale, discrepancies exist in their availability and quality at smaller geographic scales. While moderate progress has been made towards integrating these different types of data at common local scales, much work remains to make this data useable and accessible to a broad range of hydrologic investigations. The proposed hydrological observatory would make high quality data available for the smallest possible geographic scales across the High Plains Aquifer, building upon GRoWE's collaborative efforts and involving additional scientists throughout the region.

3. Proposed Core Data

The core data to be collected for this High Plains Aquifer Hydrologic Observatory should support a broad range of hydrologic investigations related to the seven areas of advancement on pages 2-3 of this prospectus. Three primary data collection themes are:

1. Employing new and existing methodology to collect core data from local field scale to regional observations.
2. Merging core data with existing information into a comprehensive geodatabase model served to the entire region using established, standardized methodology (e.g., Maidment, 2002; Strassberg and Maidment, 2004).
3. Coordinating instrumentation and modeling at consistent scales, enabling site specific information to blend within a systematic analysis of the hydrologic cycle and its interactions with other natural processes and human systems.

Two key types of hydrologic data are currently incomplete and fragmented across the High Plains Aquifer and should be augmented within the proposed observatory: (1) accurate, real-time measurement of groundwater elevation and (2) field-level measurements of water fluxes (recharge and ET). An automated system that provided real-time data across the entire aquifer would reveal new comprehensive hydrologic understanding from local to regional scales as interrelated with soil type, climate, vegetation and land use. Flux data are necessary to understanding functioning, variability and scalability of aquifer hydrology.

Changes in aquifer storage can be studied by focused monitoring efforts at a network of benchmark sites to collect core data throughout the High Plains Aquifer. The use of benchmark sites is one of the principle recommendations in the report *Groundwater Fluxes Across Interfaces*, recently published by the National Academy of Sciences (NRC, 2004). Motivation for this approach lies in the fact that few large-scale field campaigns have been conducted with the sole purpose of gathering data for the estimation of recharge or depletion. Various methods for estimating changes in aquifer storage have been employed in isolated studies, but few large-scale studies have been undertaken that permit coordinated implementation of a variety of methods and approaches. The scientific issues to be addressed using recharge estimates require benchmark sites of watershed or river-basin scale; however, smaller spatial scales may be appropriate where focused recharge is of interest.

Benchmark sites should be selected to include the range of geological, climate and landscape types within the High Plains Aquifer, described earlier. Sites should be located where historical data on stream flow, water table elevation, precipitation, and land use practices are available. Methodology to be employed might vary between sites but should include many of the following components:

- Installation of monitoring wells and pressure based depth recorders to permit continuous, automated monitoring of groundwater levels across the site (e.g., watershed).
- Continuous monitoring of flows from major discharge locations throughout the site.
- Installation of automated meteorological stations to record precipitation and estimate ET.
- Use of pedotransfer function approaches to estimate soil hydraulic properties from existing soils databases.
- Estimation of runoff using land surface topography and soil hydraulic properties, coupled with surface water modeling.
- Use of remote sensing technique to estimate land use and vegetative cover.
- Coupling of above methods to obtain long-term water balance for the land surface.
- Estimation of fluxes in the unsaturated zone using environmental isotopes, applied tracers, and temperature-based inverse methods.
- Quantification of focused recharge from streams or surface water bodies (e.g., playa lakes) within the watershed or study area.
- Use of coupled groundwater and surface water models to synthesize data collected throughout the study site and to identify needs for additional data collection.
- Use of core benchmark data to test new methods of quantifying recharge.

Given the spatial extent of the High Plains Aquifer and the need to quantify the natural and social system interactions within the hydrologic system, remotely sensed data has to play a critical role. NASA's Earth Observing System (EOS), NOAA, USGS, NRCS, National Geophysical Data Center (NGDC), National Biological Information Infrastructure (NBII) and multiple state agency data resources, products and methods could be utilized for characterization, classification and change detection purposes within the observatory. The observatory could coalesce partnerships, data, and results from a variety of potential sources and partners including: national and state surveys, research centers and groups such as KARS (Kansas Applied Remote Sensing Program), the Great Plains Regional Earth Science Applications Center, CALMIT (Center for Advanced Land Management Information Technologies), High Plains Regional Climate Center (HPRCC), National Drought Mitigation Center; and projects such as the HYper SPatial Imagery of Rural Environments (HYSPIRE), Human-Environment Regional Observatory (HERO) Network, GAP Analysis and the Green Report.

4. Example Science Questions

The proposed High Plains Aquifer Hydrologic Observatory would provide tools and methodology for a broad range of scientists to address a diversity of hydrologic phenomena, such as,

1. *Recharge and Evapotranspiration*: What relationships exist between soil type, vegetation and global climate, and the percolation of water and nutrients through and past the root zone to the phreatic surface?
2. *Surface Water/Groundwater Exchange in Dynamic Riparian Corridors*: How do fluxes of water, nutrients and contaminants between the aquifer and atmosphere change over time?
3. *Ecological Role of Vegetation in the Hydrologic Cycle*: What are the biological influences of phreatophytes in deep percolation of recharge within ephemeral streams?
4. *Human Systems and the Hydrologic Cycle*: How is the diversity of human systems that have developed in the region related to spatial variance in the hydrologic cycle, and how is the long-term sustainability of human systems mediated by the hydrologic cycle?
5. *Multi-Scale Monitoring, Modeling & Analysis*: What are the tradeoffs among various operating environments, observational and data collection methods in terms of the predictive abilities of a variety of modeling tools?
6. *Climate Change Studies*: What are the impacts of hydrologic extremes on the hydrologic cycle, vegetation and human systems?
7. *Utilization of Remote Sensing Technology*: What are the best locations to heavily instrument fieldscale observations, and what is the best methodology to meld measurements at key sites with information from higher scales (satellite imagery)?

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Bibliography

Hecox, G. R., D. O. Whittemore, R. W. Buddemeier and B. B. Wilson, 2002, Best estimates of aquifer recharge: magnitude and spatial distribution, *KGS Open File Report* 2002-25B.

Hooper, R. P., K. H. Reckhow and L. E. Band, 2004, *Designing a Network of Hydrologic Observatories,* (online at www.cuahsi.org).

Leatherman, J. C., H. A. Cader and L. E. Bloomquist, 2003, When the Well Runs Dry: The Value of Irrigation to the Western Kansas Economy, *Kansas Policy Review*.

IPCC (Intergovernmental Panel on Climate Change), 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. New York: Cambridge University Press, 881pp.

Maidment, D. R., 2002. *Arc Hydro GIS for Water Resources*, Redlands: ESRI Press.

McGuire, V.L. and B. C. Fischer, 1999, Water-level changes, 1980 to 1997, and Saturated Thickness, 1996-1997, in the High Plains aquifer: *U.S. Geological Survey Fact Sheet* 124-99, 4 p.

Montaigne, F., 2002, Water Pressure, *National Geographic*, 2-33, September.

NASS (National Agricultural Statistics Service), 1999, Catte: Final Estimates 1994-98. *Statistical Bulletin Number 953*, Washington, D.C.

NRC (National Research Council), 2004, *Groundwater Fluxes Across Interfaces*, Washington D.C.: National Academies Press.

Strassberg, G. and D. R. Maidment, 2004, Arc Hydro Groundwater Data Model, Geographic Information Systems in Water Resources III, *AWRA Spring Specialty Conference*, Nashville, May 17-19.

Steward, D. R. and E. A. Bernard, 2004, The synergistic powers of AEM and GIS geodatabase models in water resources studies, in review by *Ground Water*.

UNESCO (United Nations Educational, Scientific and Cultural Organization), March 2003. *Water for People, Water for Life - UN World Water Development Report*, UNSECO Publishing, Berghann Books, UK, (www.unesco.org/water/wwap).

White, S. E., 1992, Population Change in the High Plains Ogallala Region: 1980-1990, *Great Plains Research* 2: 179-197.