Hydrologic Observatory for the Republican River Basin/High Plains Aquifer: A Barometer for Global Climate Change

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Cooperating agencies: U.S. Geological Survey, Natural Resources Conservation Service (USDA)

I. Spatial Extent of Hydrologic Observatory

A. Scientific Rationale for Design

The proposed Hydrologic Observatory (HO) for the Republican River Basin/High Plains Aquifer (Figure 1) affords excellent opportunities for investigating hydrologic and ecosystem responses in a type area of the United States that is particularly susceptible to the impacts of global climate change. The HO includes a representative portion of the High Plains aquifer (the largest ground-water system in North America) and the largest river basin that is entirely enclosed within that aquifer. It is within an area of prime agricultural importance to the world. It can serve as a world barometer for global climate change and concomitant land- and water-use changes because it includes a single physiographic province (Great Plains) and is located in a climatic transitional area where biomass response to moisture change is proportionately greater than in arid and humid climates. In addition, it is a large enough area to allow averaging of local extremes but small enough to permit detailed determination of the water budget given the funding level for HOs. CUASHI has identified five topics as the highest priority for HO studies: 1) linking hydrologic and biogeochemical cycles, 2) sustainability of water resources, 3) hydrologic and ecosystem interactions, 4) hydrologic extremes, and 5) fate and transport of contaminants. The area and setting of the proposed HO is very appropriate for designing studies to address the following issues under each of the CUAHSI priority topics:

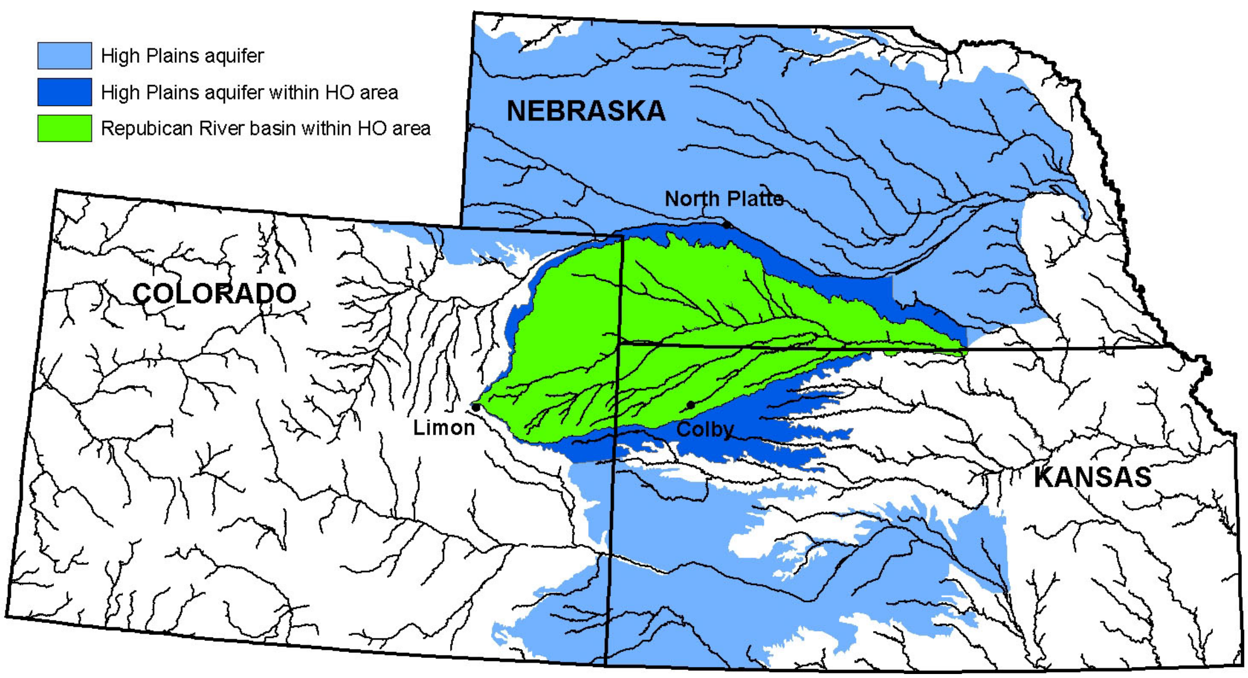

Figure 1. Republican River basin and the extent of the High Plains aquifer included within the proposed Hydrologic Observatory.

1. *Linking hydrologic and biogeochemical cycles*: The atmosphere, biosphere, soil, and surface- and ground-water components of the water budget are all important in carbon and nitrogen biogeochemical cycles. Long-term global increases in carbon dioxide are buffered by biosphere interactions. There is a feedback from biosphere mass to long-term changes in carbon dioxide concentration, temperature, and the water cycle. The impact of agricultural practices on the sequestration of carbon in soils is an area of current research in the region. Linking this work to the hydrologic cycle is necessary to understand and assess the importance of agricultural practices for carbon sequestration. Nitrogen transformations within the atmosphere, soils and sediments, plants, and surface and ground water are all key components of the nitrogen biogeochemical cycle. Better quantification of the transport of different nitrogen species in the biogeochemical cycle are needed for determining the impact of agricultural management practices on nutrient content of water (as a contaminant or eutrophication agent) and the nitrogen species composition of the atmosphere (impacting air pollution).

2. *Sustainability of water resources*: The sustainability of water resources in the High Plains aquifer is a key issue for the nation. The High Plains aquifer is the largest ground-water system in North America, providing about 30 percent of the ground water used for irrigation in the United States. The region overlying the aquifer is one of the most important agricultural areas in the United States, comprising approximately 20 percent of the nation's irrigated land. Consumption of ground water in the aquifer, primarily for irrigation, at a faster rate than capture of recharge has caused significant declines in water levels across large portions of the area. In addition, these declines have caused substantial long-term decreases in streamflow in many areas. In some cases, these changes have led to interstate disputes concerning management of water resources. The HO is designed to include a representative portion of the High Plains aquifer and the largest river basin that is entirely enclosed within its boundaries. Water-level declines caused by ground-water pumping are substantial in parts of the aquifer underlying the HO and have led to reductions in ground-water discharge and thus reductions in streamflow (Figure 2). The river is ground-water fed in its headwaters, which means it is quite sensitive to climate change and ground-water withdrawals. However, the streamflow reductions that have resulted are not completely irreversible. This is in contrast, for example, to southwest Kansas where water-level declines in the aquifer have been so great that they have essentially eliminated all ground-water discharge from the aquifer to the Arkansas River. Other rivers crossing the High Plains aquifer either have substantial watershed areas outside the aquifer extent (i.e., the Canadian River in Texas), have not been appreciably affected by ground-water pumping (i.e., in the Sand Hills area of Nebraska), or are substantially smaller (i.e., Texas). Thus, the Republican River

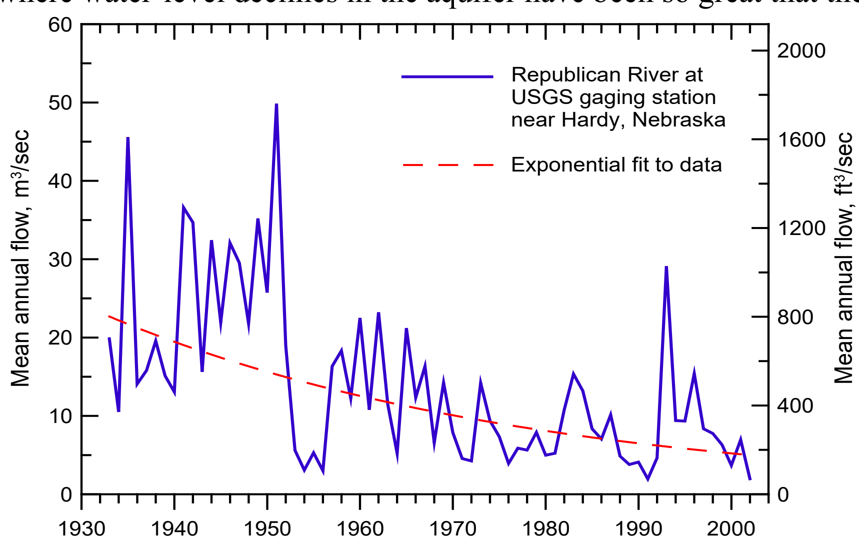

Figure 2. Change in flow in the Republican River near the Kansas-Nebraska line.

watershed represents an intact regional river system completely overlying the High Plains aquifer where the human impacts on the system are substantial enough to be easily observed, but not so great that they cannot be managed to achieve a sustainable water resource. The basin represents a part of the aquifer system in transition, but affords the opportunities to affect that transition significantly through management based on the concept of long-term sustainability of water resources. Recharge is a key component of the water budget of the High Plains aquifer system for which there is appreciable uncertainly. The HO is a region of the High Plains aquifer that includes substantial areas in which different types of recharge are believed to be important. The determination of recharge mechanisms in the HO will have very significant practical ramifications for the High Plains aquifer.

3. *Hydrologic and Ecosystem Interactions*: The direct and indirect impact of both natural and agricultural vegetation on the water budget is substantial and plays a critical role in determining whether the present water resource system is sustainable. Better quantification of the role of different types of natural and agricultural vegetation in the water budget of a large river basin/aquifer area is needed for management based on resource sustainability. For example, riparian vegetation, particularly phreatophytes, can consume a substantial amount of ground water and can significantly impact streamflow, including producing diurnal variations in streamflow in selected stream reaches. The semiarid region of the HO is especially sensitive to long-term climate changes because small changes in temperature, precipitation, and potential evapotranspiration, and the frequency patterns in these variables, can have a substantial impact on the ecology, streamflow, and ground-water use, and, therefore, the social and economic stability of the region. The biomass of the Great Plains type area has a greater response to changes in moisture than arid areas, where there is little biomass, and than wet areas, where there is a surplus of moisture. Declines in ground-water levels have shortened the average length of perennially flowing streams in the HO, thereby changing the character of riparian vegetation, which then impacts the hydrology and transpiration within the stream valley. Ground-water declines causing baseflow reduction in headwater areas also greatly affect the habitats of threatened fish species and migratory waterfowl. Reduction of ground-water use to achieve aquifer sustainability could lead to changes in agricultural crops and potential increases in grassland area. Long-term data are needed to better understand these interactions and to assess the impacts of land- and water-use modifications implemented to achieve aquifer sustainability. Specifically, long-term data are needed to understand the impact on efforts to buffer global climate change.

4. *Hydrologic Extremes*: The HO encompasses an area with substantial spatial and temporal variability in climate and streamflow. The mean annual precipitation changes from about 40 cm/yr along the western boundary to approximately 64 cm/yr at the eastern end. The annual precipitation in the western part of the HO has ranged from less than 20 cm/yr to over 80 cm/yr, and in the eastern end from less than 40 cm/yr to over 100 cm/yr. This spatial climatic variation results in substantial changes in ecosystems from west to east across the HO. Mean annual streamflow in the Republican River at the lower end of the HO has ranged from less than 2 m^3/sec to 50 m^3/sec during the period 1933-2002. The range in the daily mean flow has been 0.14-6,371 m^3/sec, a ratio of over 4,500 for high to low flow. These extremes afford the opportunity to examine differences in the impact of substantially different climatic conditions on ecology, agricultural land and water use, stream-aquifer interactions, and the resulting social and economic fabric of the HO area. In addition, the current large range in spatial and temporal

variability provides an excellent opportunity to examine the impact of future global climatic change.

5. *Fate and Transport of Contaminants*: Agricultural areas in the Mississippi River system contribute a substantial proportion of the nutrient flux that enters the Gulf of Mexico and produces hypoxia. The HO is representative of agricultural areas in the Great Plains region of the Mississippi basin. Additional contaminant concerns of priority in the Great Plains are the release of pesticides, especially atrazine, during runoff events, of bacteria from animal and human waste, and of sediment from cultivated fields and overgrazed grasslands. Individual states are addressing these concerns under total maximum daily load (TMDL) programs. Changes in the contaminant loads, fate, and transport are all linked to variations in the hydrologic system, both directly, in terms of variations in precipitation, and indirectly in terms of modifications in land- and water use resulting from management practices and global climate change. Data are needed to better determine the relationships and links among hydrology, land use/land cover, and contaminant generation, fate, and transport.

The HO will allow regional scale investigations that require a large area for observation and analysis. In addition, three subbasins will be more intensively studied to provide more detailed observations and comparisons within the HO. In Colorado, the subbasin is the Arikaree River watershed, which represents a headwater area in the most western and driest part of the HO and is largely a ground-water fed system. In Nebraska, the subbasin selected is Medicine Creek, which includes sand hills in its northern headwaters that provide ground-water discharge to maintain baseflow. In Kansas, the subbasin selected is the Prairie Dog Creek watershed along the southern portion of the HO to the KS-NE state line, which is now largely a rainfall runoff driven stream. Both the Kansas and Nebraska subbasins include a reservoir that will allow study of long-term impacts of surface-water impoundments on the hydrology of the area as well of changes on surface inflow supplying the reservoir water.

Two field headquarters are proposed for the HO to facilitate operation of field measurements in the subbasins. KSU operates the Northwest Research and Extension Center at Colby in the upper part of the Prairie Dog Creek watershed. UNL operates the West Central Research and Extension Center in North Platte that is relatively close to the Medicine Creek subbasin. The existing buildings and scientific staff at the research and extension centers in Nebraska and Kansas will facilitate studies by other scientists within the HO. Additional building space could be developed at these stations for specific HO staff, instrumentation, and field analysis. Facilities at CSU could serve as staging areas for field work for the Arikaree subbasin.

B. Site Characteristics

The HO includes the Republican River basin from its headwater drainage to the river near the Nebraska-Kansas state line (USGS gaging station near Hardy, Nebraska). The HO lies entirely within the Great Plains physiographic province. The Republican River watershed in the HO covers 58,000 km^2. The area of the High Plains aquifer to be included in the HO is larger than that of the Republican River watershed in order to encompass the natural division of the aquifer between northwest and west-central Kansas and to include aquifer areas that interact with those within the HO. The Republican River basin is the largest river system entirely enclosed within the High Plains aquifer, the largest ground-water system in North America. Although the HO area is several times greater than the minimum size of 10,000 km^2 suggested for an HO, the area is an appropriate size for a basin in a semi-arid region that requires a large area to produce a river of reasonable size at the downstream end. This is in contrast to a smaller watershed in a humid region that generates substantially more runoff per area, such as the Neuse River. For comparison, the mean long-term annual flow of the Neuse River near its mouth is nearly 100 m^3/sec, while that of the Republican River at the downstream end of the HO is approximately 14 m^3/sec.

The headwater tributaries in the HO are distributed across the High Plains of northeastern Colorado and western Kansas and Nebraska (Figure 1). The Arikaree River and the North Fork of the Republican River join in the southwest corner of Nebraska to form the main stem of the Republican River. Tributaries originating in northeastern Colorado and western Nebraska flow to the southeast to join the northern side of the main stem. Tributaries originating primarily in northwestern Kansas flow in a northeastern direction to join the south side of the main stem. The mean annual runoff ranges from less than 0.5 cm in the western area of the HO to about 7 cm at the eastern end. The minimum and maximum annual precipitation and streamflow are substantially different from the long-term average as indicated earlier.

The surface geology consists primarily of the Ogallala Formation of Tertiary age. Deposits of loess cover the Ogallala sediments in many areas and form soils with very good properties for agricultural crops. Quaternary alluvial sediments overlie the Ogallala Formation in the Republican River valley. Sand and gravel comprise a major part of these unconsolidated deposits, and form the important aquifers of the HO. Upper Cretaceous bedrock, consisting primarily of shale, limestone, chalk, and sandstone, underlies the Ogallala Formation. The regional direction of ground-water flow is generally from west to east in response to the topographic slope of the plains (http://capp.water.usgs.gov/gwa/gwa.html).

The saturated thickness of the High Plains aquifer within the HO ranges from zero near its boundary to a maximum of nearly 100 m in northwestern Kansas, 120 m in northeastern Colorado, and over 150 m in southwestern Nebraska near the Platte River. Yields of irrigation wells can be greater than 3 m^3/min in a major part of the HO. The total number of active supply wells in the Kansas and Colorado portions of the HO has been level since the early 1980s at a total of approximately 4000 in each state, but has been rising since that time in Nebraska to a current total of about 18,000, although the current rate of increase is much less than in the 1960s and 1970s (http://www.republicanrivercompact.org/v12p/RRCAModelDocumentation.pdf). The annual average volume of water pumped from the High Plains aquifer within the HO was 3.1×10^9 m^3 during the decade of the 1990s. In comparison, potential evapotranspiration associated with phreatophyte areas in the HO has been estimated as 0.6×10^9 m^3. Water-level declines caused primarily by ground-water pumping have occurred in the aquifer in all three states of the HO; the declines are over 30 m in parts of the HO. The ground-water level has risen in a zone south of and paralleling the Platte River within the HO as a result of water diverted from the river for irrigation; rises have exceeded 10 m in part of this zone. Within the HO, current depths to ground water range from less than a couple meters in the alluvial aquifer next to flowing streams to over 70 m in parts of the High Plains aquifer.

Recharge to the High Plains and alluvial aquifers occurs in different forms, from precipitation, from seepage through soils irrigated with ground water or surface water, and from leakage from canals and laterals in surface-water diversion areas. Estimates of aquifer recharge in the HO range widely, depending on the land use, land cover, and soil, from less than 0.1 cm/yr to over 10 cm/yr.

Ground water in both the High Plains and alluvial aquifers is generally very fresh, except for waters in the alluvial aquifers of some of the tributary valleys where total dissolved solids are higher as a result of concentration by evapotranspiration. The surface waters are also fresh, although the dissolved solids concentration is substantially smaller during peak flows in comparison to baseflows from ground-water discharge.

The watershed is in an area of substantial agricultural cropland that includes extensive irrigation. The percentage of irrigated land surface ranges from less to 5% to over 25% within the HO in all 3 states and reaches over 50% in part of the eastern portion of the HO in Nebraska. The primary land use in non-irrigated areas is also agricultural, and includes dryland farming, rangeland, and farmland in Conservation Reserve Programs.

II. Existing Data Infrastructure

A. Climatic and weather observatories:

There are over 100 National Weather Service stations in the HO area. The High Plains Regional Climate Center (HPRCC), http://hprcc.unl.edu/index.html, which includes UNL (headquarters), CSU, and KSU among 7-state university affiliates, operates an automated weather data network with 14 stations in the HO. The Community Collaborative Rain and Hail Study (CoCoRaHS) network records rain, hail, and snow data, and the Colorado Agricultural Meteorological Network (CoAgMet) stations collect weather data within the HO area; data can be accessed from the CSU Colorado Climate Center http://www.atmos.colostate.edu/.

B. Streamflow and reservoir stations

The U.S. Geological Survey (USGS) maintains 24 surface-water gaging stations in the HO area (http://waterdata.usgs.gov/ne/nwis/sw), (http://waterdata.usgs.gov/ks/nwis/sw), (http://waterdata.usgs.gov/co/nwis/sw). The Nebraska Department of Natural Resources (NDNR) operates an additional 14 stations. Reservoirs and canals in the HO are also gaged (http://www.accesskansas.org/kda/dwr/Interstate/Republican_River_data.htm).

C. Surface-water quality monitoring stations

State and local agencies monitor stream-water quality at various frequencies for many sites. For example, the Kansas Department of Health and Environment (KDHE) has nine stations within the HO (http://www.kdhe.state.ks.us/tmdl/upperrepublican.htm). There are older, long-term water-quality records of the USGS for many of the same sites.

D. Ground-water data

1. *Water-level measurements*: The Kansas Geological Survey (KGS) at KU and the Kansas Department of Agriculture (KDA) annually measure water levels in over 340 wells within the HO. The data are captured electronically in the field and are provided in an interactive database at http://www.kgs.ku.edu/Magellan/WaterLevels/index.html. Groundwater Management District No. 4 (GMD4) in Kansas, which encloses most of the HO area in Kansas, measures water levels as well. The four Natural Resource Districts (NRDs) within the HO in Nebraska monitor water levels in nearly 700 wells. In Colorado, the Arikaree Ground Water Management District and the Colorado Department of Natural Resources also collect water-level data.

2. *Water-use data*: The KDA requires water-use reports for all production wells permitted in Kansas and maintains a database of the information. Most of the wells in the HO area have meters and regulations in Nebraska and Kansas call for increased metering of water use.

3. *Water well log data*: The KGS maintains an online data base of water well completion records (including lithology) at http://www.kgs.ku.edu/Magellan/WaterWell/index.html.

4. *Ground-water quality*: The NRDs in Nebraska collect ground-water quality data for over 100 wells in the HO. The KDHE has monitored ground-water quality for over 30 wells in the

HO. The USGS previously collected and analyzed samples for many of these same wells and has also sampled a large number of other wells during the last 60 years.

E. Republican River Compact Administration (RRCA) ground-water model: Nebraska, Kansas, and Colorado have a compact for administering water use within the Republican River system. In 2003, the RRCA accepted the use of a numerical ground-water model for helping in the administration of water (http://www.accesskansas.org/kda/dwr/Interstate/RRCAGWModel.htm). The model boundaries are essentially the same as those of the HO. The states are now annually updating the data input to the model for use in administering water in the basin.

F. GIS data coverages: The Data Access and Support Center (DASC, http://gisdasc.kgs.ku.edu/) for Kansas at the KGS provides online access to digital data for a wide variety of GIS coverages in the HO area. In addition, several different sources of GIS data are available from departments and institutes at CSU, UNL, and KSU. These include the Center for Advanced Land Management Information Technologies (CALMIT) at UNL, http://calmit.unl.edu/calmit/.

G. Remote sensing: The Kansas Applied Remote Sensing (KARS) Program (http://www.kars.ku.edu/) at KU conducts research on environmental and agricultural applications of remote sensing technology. KARS provides the Green Report, an online system for providing remotely sensed images throughout the growing season to monitor the progress and relative conditions of crops and natural vegetation throughout the conterminous United States. CALMIT at UNL also conducts research and education for remote sensing of land-surface characteristics. A variety of research groups and departments at CSU and KSU apply remote sensing to atmospheric properties and land cover studies within the HO.

H. Water research in the High Plains: KU, KSU, UNL, and CSU all have many departments involved in water research, some of which include the HO area. The UNL Water Center (http://watercenter.unl.edu/), the Colorado Water Center (http://watercenter.colostate.edu/overview.html), and the Kansas Center for Agricultural Resources and the Environment (KCARE, http://www.oznet.ksu.edu/kcare/) coordinate and facilitate water-related research. The KGS has been conducting research on the High Plains aquifer for many years (http://www.kgs.ukans.edu/HighPlains/index.htm).

I. Agricultural research: KSU, UNL, and CSU all have strong departments conducting field research and obtaining data related to agriculture in the HO. These studies include water use and conservation associated with crop types and different irrigation systems, and the impacts of agricultural wastes on soil chemical, biological, and physical properties and on surface and ground-water quality. KSU is the lead institution in the Consortium for Agricultural Soils Mitigation of Greenhouse Gases, which seeks to mitigate greenhouse gases in the atmosphere through carbon sequestration strategies. The federally-supported consortium includes KSU, UNL, CSU, and six other universities, and a national laboratory, in conjunction with research groups within the USDA. KSU maintains the Northwest Research–Extension Center (http://www.wkarc.org/Nwrec/nwrec.htm) at Colby within the HO, and UNL has the West Central Research and Extension Center at North Platte (http://westcentral.unl.edu/) on the northern boundary of the HO.

J. Ecological research: CSU, UNL, KSU, and KU all have departments involved in ecological research either within or applicable to the HO. For example, KSU has an NSF-funded program for Long Term Ecological Research (LTER) conducted at the Konza Prairie Natural Research Area that includes water-related research applicable to the HO. The Central Plains Center for Bioassessment at the Kansas Biological Survey at KU (http://www.kbs.ku.edu/) has a research emphasis on monitoring the ecological health of streams. The UNL Initiative in Ecological and Evolutionary Analysis (http://ecology.evolution.unl.edu/) includes a field research site within the HO. A Colorado example is a CSU study related to fish in the Arikaree River watershed.

K. Economic and social science data and studies

1. *Economic data*: Data are available for agricultural-derived income and its relationship to best management practices for irrigation, crop types, waste control and other agricultural activities. Economic research related to agriculture and water resources is conducted at KSU, KU, UNL, and CSU. For example, UNL just completed a study on the potential economic impacts of reducing ground-water use in the Republican River basin in Nebraska to achieve legal limits of consumption.

2. *Social data*: KSU geographers are involved in a multi-university research project studying regional change (Human-Environment Regional Observatory [HERO], http://hero.geog.psu.edu/index.jsp. There are four HERO observatories in the U.S., one of which is the High Plains of Kansas. The National Drought Mitigation Center at UNL (http://drought.unl.edu/index.htm) helps people and institutions develop and implement measures to reduce societal vulnerability to drought.

III. Proposed Core Data

A. Water budget and fluxes

1. *Weather and climatic measurements* – surface weather stations, radar, and atmospheric measurements

2. *Surface evaporation and plant transpiration* – pan evaporation, sap flow and vegetation canopy measurements, remote sensing of vegetation and soil moisture, water-table monitoring in riparian zones of streams

3. *Vadose zone water and transfer* – instrumented lysimeters and boreholes, remote sensing of soil moisture

4. *Aquifer recharge and ground-water storage* – ground-water level measurements, geologic weighing lysimeters involving deep instrumented boreholes, surface and remote sensing (GRACE) microgravity, tracer and isotopic measurements, water-budget models

5. *Ground-water discharge to streams* – ground-water level measurements in stream valleys, seepage measurements along stream segments

6 *Streamflow* – flow gaging stations

7. *Surface- and ground-water use* – metered diversions and pumping wells, remote sensing of crop types and health correlated with land-based measurements of use

8. *Subsurface ground-water inflows and outflows* – ground-water level measurements, chemical and isotopic measurements in deep boreholes, water-budget calculations from modeling

B. Water-quality budgets and fluxes

1. *Constituents and properties of focus* – Dissolved SiO_2 and N and P species (fluxes affecting Gulf of Mexico hypoxia); conductance, major dissolved constituents, Br, B, and selected isotopes (for chemical determination of water-balance changes); bacteria and pesticides (for the TMDL process)

2. *Observations and data* – Sampling and analysis of rainfall, stream and lake water, ground-water, and soils at a frequency appropriate for most efficient determination of fluxes; microbiological characterization of bacteria for source determination; fertilizer and pesticide application data

C: Carbon and nitrogen cycling:

1. *Atmospheric component* – Periodic sampling and analysis of atmospheric gas and precipitation; weather data for computation of influx to and outflux from HO area

2. *Vegetation and soil component* – Periodic sampling and analysis of soils, soil gas and moisture, plants, and animal wastes; estimation of other environmental and anthropogenic components from existing data and selected sampling and analysis

D. Economic and social sciences

1. *Economic data* – Assembly of existing economic data for agriculture and other industries, collection of new economic data needed to improve relationship to climate and water budget changes in basin

2. *Social data* – Application of the methods used in the HERO project (see Sec. II, K, 2 above) to the HO area; surveys for determining actual and anticipated effects resulting from climate and water-budget changes that impact water-use and agricultural practices

IV. Example Science Questions

A. What are the impacts of global climate change on the hydrologic cycle of a regional river basin and the underlying High Plains aquifer in the Great Plains? To determine this, the following issues need to be addressed: What is the magnitude of weather variations on the current water budget and what are the uncertainties? What is the magnitude of anthropogenic effects (such as ground-water withdrawals, atmospheric moisture changes from irrigation and land-cover alterations, terracing and small ponds, etc.) on the current water budget and what are the uncertainties? What are the roles of different types of natural and agricultural vegetation in the water budget, including how important are invasive phreatophyte species in riparian zones in affecting shallow ground water and stream flow? What are the measurements and the frequency of observations needed to reduce the uncertainties in quantifying environmental and anthropogenic functions so that the effects of global climate change can be discerned? What new technology can be applied to address the largest uncertainties? How do the answers to these water budget questions compare to those for other hydrologic observatories in the U.S.? What are the adjustment and scaling factors necessary to apply the answers to these questions to other watersheds and aquifers? How effective is the HO as a barometer of global climate change? Are streamflow data the best regional barometer for assessing the global climate impacts, and, if so, what is the most sensitive characteristic of streamflow to be used as the barometer?

B. What are the most important components of the water budget for the purposes of understanding how to sustain the water resources of the Great Plains over the long term and what is the uncertainty in the characterization of those components? To determine this, the following issues need to be addressed: What are the long-term changes in ground-water storage in the High Plains aquifer and what are the uncertainties in the methods for quantification of these changes? What is the quantitative contribution of focused ground-water recharge from ephemeral stream drainages, playas, and irrigated fields in comparison to areal recharge across the HO? How has recharge to the High Plains aquifer changed as a result of changes in land- and water-use, land-cover, and topography? Can geologic weighing lysimeters, surface microgravity, tracer and isotopic measurements, and GRACE remote sensing be used to improve current estimates of recharge? How important are heterogeneities in the hydrostratigraphy of the High Plains aquifer for determining the rate of water-level declines, and what uncertainty does this introduce to computations of ground-water storage based on water-level changes?

C. What is the long-term biomass change resulting from global climate change in the Great Plains environment and what is the magnitude of the feedback from biosphere mass to long-term trends in the hydrologic cycle and in the carbon and nitrogen biochemical cycles? To determine this, the following issues need to be addressed: What is the impact of agricultural practices on the sequestration of carbon in soils in the Great Plains and, thereby, on the biochemical cycle of carbon and concentration of carbon dioxide in the atmosphere? How do biomass changes caused by global climate change and agriculture practices aimed at improving carbon sequestration change the biochemical cycle of nitrogen? What are the links between the carbon and nitrogen cycles and budgets to variations, especially extremes, in the hydrologic cycle? Can variations in the carbon and nitrogen budgets of a Great Plains basin be separated into components controlled primarily by precipitation changes versus those controlled primarily by agricultural practices? How effective is long-term biomass change in such a transition region as a barometer of climate change?

D. What are the most important mechanisms controlling ground-water contamination caused by recharge through the vadose zone of the High Plains aquifer? To determine this, the following issues need to be addressed: What is the relative importance of focused recharge below irrigated fields, playas, and ephemeral stream drainages, in comparison to areally distributed recharge for transporting contaminants? What is the relative importance of discrete sources of contamination, such as waste lagoons and flow down the gravel packs of large diameter wells, versus more areally distributed sources? What new technology can be applied to better quantify the role of discrete versus areal sources of contamination?

E. What are the variations in and the major controls on the nutrient, bacteria, pesticide, and sediment fluxes from an area in the Great Plains in which there is substantial agricultural production? To determine this, the following issues need to be addressed: What is the character of the nutrient flux (N/P ratios and relationship to SiO_2) and its link to hydrologic variations, and how important is this flux in contributing to the hypoxia in the Gulf of Mexico? Can the sources of bacteria in surface waters, one of the greatest concerns in the TMDL process in Great Plains states, be discerned well enough through scientific advances to allow refinement of best management practices to substantially reduce concentrations?

F. What are the economic implications of the alterations in water use and agriculture needed to achieve sustainability of the High Plains aquifer and the surface waters interacting with it? To determine this, the following issues need to be addressed: What impact does long-term global climate change have on these alterations and thus on the economy of the Great Plains region? What is the relationship between the economic impacts of practices directed at achieving water sustainability and those of practices aimed at carbon sequestration?

G. What are the impacts of natural (hydrologic extremes) and anthropogenic (water use and agricultural practices) changes on the ecosystem (wildlife, aquatic species, and vegetation diversity and populations)? Can these impacts be quantified well enough to discern them from the influence of global climate change?