

# Proposed Hydrologic Observatory for Texas: The San Antonio and Guadalupe Watersheds and Underlying Aquifers

Team Leaders: Bridget R. Scanlon<sup>1</sup>, Andrew Samson<sup>2</sup>, MaryLynn Musgrove<sup>3</sup>

<sup>1</sup>Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, J.J. Pickle Research Campus, Bldg. 130, 10100 Burnet Road, Austin, TX 78758-4445, bridget.scanlon@beg.utexas.edu, 512-471-4445; <sup>2</sup>International Institute for Sustainable Water Resources, Texas State University, 601 University Drive, Clevenger House, San Marcos, TX 78666, 512-245-9200, as22@txstate.edu; <sup>3</sup>Department of Geological Sciences, University of Texas at Austin, Jackson School of Geosciences (C1100), Austin, TX 78712-0254, 512-471-2457, mlm@mail.utexas.edu.

## 1. Spatial Extent of Hydrologic Observatory

### 1a. Scientific rationale for design

The proposed Texas Hydrologic Observatory (HO) includes two adjacent watersheds, the San Antonio and Guadalupe watersheds, and underlying aquifers, the Edwards and Carrizo-Wilcox aquifers (Fig. 1). This proposed system offers a wide range of conditions that make it an ideal location for an observatory. These include spatially and temporally variable climatic forcing; a large range of land uses from extremes of rural and urban; strongly linked surface and subsurface flow systems; diversity of subsurface aquifers (Edwards karst aquifer, and Carrizo-Wilcox porous media aquifer); extreme floods and droughts; and critical issues related to water resources management and endangered species. This HO will be designed to address a wide variety of scientific issues related to the water cycle such as:

- impact of land use/land cover (LULC)
- assessment of climate variability and its influence on the water cycle
- effect of hydrologic extremes
- hydrologic and nutrient cycling
- hydrologic and ecosystem interactions
- surface water and groundwater interactions.

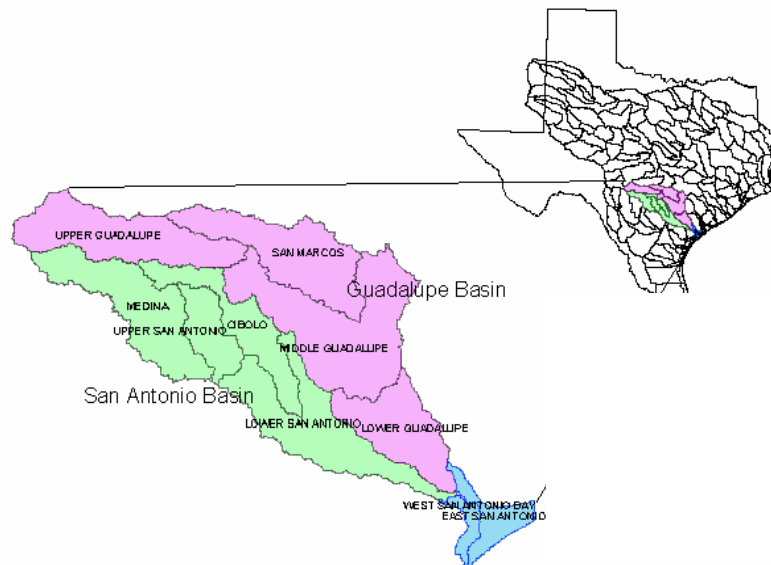


Fig. 1. Location map of proposed Texas Hydrologic Observatory, consisting of parallel basins of the Guadalupe and San Antonio basins.

The paired watersheds were chosen because they represent contrasting LULC settings and thus allow comparative research. The Guadalupe watershed is predominantly rural, whereas the San Antonio watershed includes the city of San Antonio with a current population of about 1.1 million people. Understanding relationships between past and current LULC changes and the water cycle will help predict potential impacts of future LULC changes on water resources. The climate ranges from semiarid inland on the Edwards Plateau (660 mm/yr precipitation) to subhumid at the coast (1120 mm/yr precipitation) and thus provides an excellent field laboratory to evaluate the impact of the range in climate forcing on the water cycle. The proposed HO is highly susceptible to hydrologic extremes because of the tight coupling between atmospheric forcing and surface and subsurface hydrology. Close proximity to the Gulf of Mexico results in some of the most intense rainfalls in the US (e.g.,  $\leq 750$  mm in one day). The San Antonio metropolitan area has experienced a large number of flooding tragedies. The region is also vulnerable to long-term droughts because of the extremely dynamic system and the large human and ecosystem needs for water. Developing sustainable water resources under drought conditions is extremely challenging. Maintenance of minimum spring flows is essential for endangered species habitat. The paired watershed system will provide an excellent opportunity to evaluate linkages between LULC and nutrient loading to the system. Evaluating threshold nutrient levels will also be important for assessing the vulnerability of ecosystems to excessive nutrient loading. Other water quality issues, such as increasing salinity during low flow periods related to upward movement of deep saline water into freshwater systems, are relevant for studies of coastal salt water intrusion. The proposed HO provides an excellent opportunity to evaluate hydrologic and ecosystem interactions because of tight coupling between the two and the extremely dynamic nature of the system. The proposed design will provide an excellent opportunity to advance our understanding on many critical issues related to the water cycle.

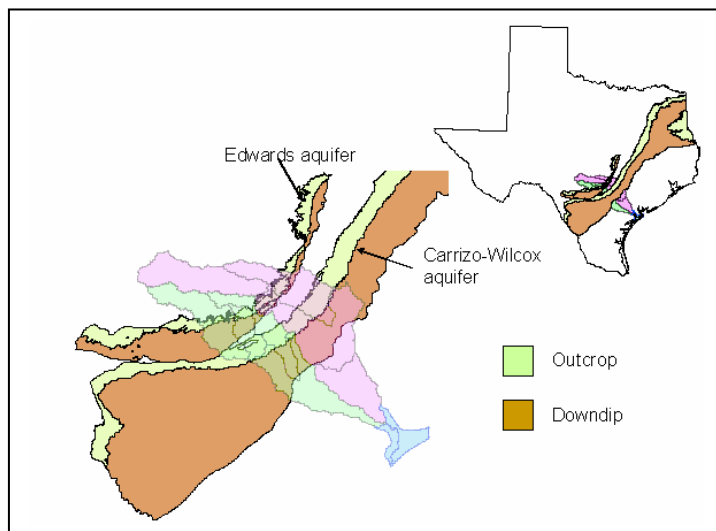


Fig. 2. Location map of proposed Texas Hydrologic Observatory, detailing underlying aquifer systems.

A state-of-the art facility is planned as a component of the HO to be housed at Aquarena Center, which is at the headwaters of the San Marcos River ( a tributary of the Guadalupe River), and part of the campus of Texas State University. Additional partners for this facility include the Texas Parks and Wildlife Department, the Guadalupe Blanco River Authority, The US Fish and Wildlife Service, The US Army Corps of Engineers and the City of San Marcos. Phase One of the project is already underway, which is restoration of the Historic Aquarena Springs Inn adjacent to Spring Lake (which is formed by the more than 200 springs discharging

on the site). Phase Two includes demolition of existing structures on the site (remaining from a historic amusement park). Phase Three is tied directly to the HO, and will include construction of a cluster of “green buildings”, including a visitor’s center with educational displays. This facility would provide an ideal center for the location of the HO infrastructure.

### **1b. Site characteristics**

The proposed HO includes two adjacent watersheds (Guadalupe and San Antonio) and two different underlying aquifer systems, the karstic Edwards aquifer, and the porous media Carrizo-Wilcox aquifer. Unique characteristics of this HO, which contribute to its suitability, include:

- Dynamic karst system that responds rapidly to climate variability and LULC change
- Strongly coupled groundwater/surface water system through aquifer recharge from surface water to groundwater and spring discharge from groundwater to surface water
- Access to the subsurface Edwards aquifer through caves for monitoring recharge
- Strongly coupled hydrologic and biologic systems shown by vulnerability of various species to varying flow conditions
- Combination of karst and porous media aquifers for providing reliable groundwater supply
- Rapid LULC change through reduced agriculture and increased urbanization
- Subject to hydrologic extremes, including floods and droughts.

The area of the proposed HO is 26,800 km<sup>2</sup> and includes the Guadalupe (16,000 km<sup>2</sup>) and San Antonio (10,800 km<sup>2</sup>) watersheds. Three distinct topographic regions can be recognized; the *upper* region, where headwaters begin at elevations of 244 – 200 m; the *middle* region, at elevations of 200 – 100 m; and *lower* region between 100 m and sea level. The climate ranges from semiarid in the upper region to subhumid in the lower region near the coast. Average annual precipitation ranges from 660 mm in the upper region to 1120 mm in the lower region. Both watersheds originate in karst limestone where spring flows provide fairly stable baseflows to the streams. The geology of the upper region includes the Edwards Plateau limestone formations whereas the middle region consists of deep layers of mixed clay and loam (Blackland) soils, and the lower region consists of alluvial sands and sandy loams. The combination of climate and geology interact to produce diverse vegetation and unique ecological communities. Distinct ecoregions from the upland to the coast include the Edwards Plateau, the Blackland Prairies, and the Coastal Plain. Evergreen forest is found in the upper region, stands of deciduous and mixed forest are present in the middle region, and coastal grasslands and emergent wetlands are found in the lower region. The primary difference in LULC in the two component watersheds is the predominantly undeveloped nature in the Guadalupe watershed (2% urban) and the highly developed nature of the San Antonio watershed (8% urban). The current population of the Guadalupe watershed (400,000) is expected to double by 2050. In contrast, the San Antonio watershed contains the city of San Antonio, a major urban center and the 3<sup>rd</sup> largest city in Texas. The basin population is estimated to increase from 1.1 million in 2000 to 3.3 million by the year 2050.

The Guadalupe River originates in the southern edge of the Edwards Plateau. It has one major reservoir (Canyon Lake; volume of 1,392 million m<sup>3</sup>) west of New Braunfels that was constructed for water supply, flood control, and hydroelectric generation. Three major tributaries contribute to the Middle Guadalupe River: the Blanco, San Marcos, and Comal Rivers along the eastern edge of the Edwards Plateau, which are fed primarily by spring flow from the underlying Edwards Aquifer. San Marcos Springs, the second largest spring system in the SW US and the headwaters of the San Marcos River, are impounded at Spring Lake, the proposed site for the Texas HO physical facilities (described above). The San Antonio River originates in the city of San Antonio and flows in a southeasterly direction. The river flows through man-made channels in downtown San Antonio, forming a popular tourism site known as the River Walk. Southeast

of downtown San Antonio, two off-channel reservoirs (Victor Braunig and Calaveras Lakes) used for hydroelectric cooling are held at constant levels by pumping water from the San Antonio River. Two major tributaries of the San Antonio River are the Medina River and Cibolo Creek. The major reservoir, Medina Lake was constructed for irrigation. The San Antonio River joins the Guadalupe River approximately 16 km before entering Guadalupe Bay.

The major aquifers include the Trinity, Edwards-Trinity, and Edwards-Balcones aquifers in the Upper Guadalupe basin; with the Edwards-Balcones karst aquifer being the major source of groundwater (commonly called the Edwards aquifer). The middle and lower portions of both basins are supplied by groundwater from porous media systems including the Carrizo-Wilcox, Queen City, Sparta, and Gulf Coast aquifers. The proposed HO will include the Edwards and Carrizo-Wilcox aquifers.

## **2. Existing Data Infrastructure**

The watersheds and subsurface aquifers in the proposed HO have a voluminous and diverse existing data infrastructure. A website is currently being developed to describe all existing data sources and will be available in mid-August. More than 20 organizations are active in data collection and analysis including river basin authorities, aquifer conservation districts, cities, universities, and federal, state, and local agencies. Many of these organizations are collaborating organizations in the proposed HO team. A general review, though by no means thorough listing of the existing data infrastructure includes:

- South Central Texas is an active region of the US Geological Survey's (USGS) national water-quality assessment program (NAWQA), which since 1995 has collected streamflow, water quality, land use, evapotranspiration (ET), ground water, fish and aquatic biology data at a number of sites (<http://tx.usgs.gov/sctx/>).
- The USGS, in conjunction with the Edwards Aquifer Authority (EAA; one of the largest groundwater conservation districts) operates a network of about thirty ground water level and water quality monitoring wells to detect urban land use impacts. This is relevant for the proposed HO because much of the upper watersheds in the two river basins are located in karst topography with significant population growth occurring over sensitive areas. The EAA ([www.edwardsaquifer.org](http://www.edwardsaquifer.org)) has an extensive aquifer science program that includes a wide range of aquatic biology research as well as an extensive network of precipitation, groundwater monitoring wells, and stream discharge stations to support aquifer recharge, rainfall modification, synoptic groundwater levels, and environmental sampling programs.
- The National Oceanic and Atmospheric Administration (NOAA) has calibrated NEXRAD stations throughout the area as well as about 98 active COOP rain gauges (several recording) in the region.
- The Texas Water Development Board (TWDB, [www.twdb.state.tx.us](http://www.twdb.state.tx.us)) is involved in water planning and data collection and has extensive surface and groundwater data records. The TWDB has an ongoing initiative to develop Groundwater Availability Models (GAM, numerical groundwater flow models) for all aquifers of Texas. Models have been developed for the Edwards and Carrizo Wilcox aquifers.
- Two large river basin authorities – the San Antonio River Authority (SARA; [www.sara-tx.org](http://www.sara-tx.org)) and the Guadalupe-Blanco River Authority (GBRA; [www.gbra.org](http://www.gbra.org)) have been in existence since the 1930's. SARA has extensive streamflow, water quality, and biomonitoring stations throughout its region and has a new program to collate all data and information into an ArchHydro data model with modeling components for the entire river basin. GBRA, likewise, has an extensive streamflow network, a 50-site rain gauge network, and a water quality monitoring network. GBRA is also active in groundwater issues.

- The largest water utility in the San Antonio region is the San Antonio Water System (SAWS; [www.saws.org](http://www.saws.org)). SAWS has extensive groundwater level and water chemistry monitoring stations and is concerned with the saline zone interface of the Edwards aquifer.
- Universities in the region include The University of Texas at San Antonio ([www.utsa.edu/water](http://www.utsa.edu/water)), and CUASHI partners of The University of Texas at Austin, Texas State University in San Marcos, and Texas A&M University. Each university has programs and active research that will provide further varied data infrastructure for the proposed HO. Several examples include:
  - The Center for Research in Water Resources at UT-Austin ([www.crrw.utexas.edu](http://www.crrw.utexas.edu)) has constructed an ArchHydro database of the entire Guadalupe River Basin
  - Texas State University-San Marcos is currently conducting a multidisciplinary hydrologic investigation in the Blanco River Basin with four aquatic biology elements, hydrology elements including SWAT watershed modeling, and a socio-economic element. Data collection in Sink Creek Watershed in the headwaters of the San Marcos River at the Freeman Ranch by the University includes three eddy covariance sites and ET sites associated with three different vegetation communities (details available at: [www.swt.edu/iiswr](http://www.swt.edu/iiswr), [www.eardc.swt.edu](http://www.eardc.swt.edu), [www.aquaticresources.bio-txstate.edu](http://www.aquaticresources.bio-txstate.edu))
  - The Bureau of Economic Geology at UT Austin ([www.beg.utexas.edu](http://www.beg.utexas.edu)) has extensive reports describing data and research in the Edwards aquifer region, geologic structure, and vegetation coverages. The Bureau developed a virtual reality demonstration of the Edwards Aquifer that is shown in the Whittey Museum for education purposes.
  - The Agricultural Research and Extension Center at Uvalde, Texas, of Texas A&M University, operates ten precipitation interception vegetation sites and has weighing lysimeters.
  - New monitoring equipment is currently being installed by CUAHSI partners at Spring Lake, the site of San Marcos Springs. Data collected via GOES satellite will include meteorological data for ET calculations, net radiation, soil moisture, water level, and watershed inflow/outflow. Updates for spring orifice flow and chemistry monitoring and saline/freshwater well monitoring are scheduled to be added in 2005.
  - Ongoing research by UT-Austin and Texas A&M at Freeman Ranch, within the HO boundaries, currently consists of direct measurements of ET, carbon and energy fluxes using eddy covariance in three different land covers on the Edwards Plateau. Towers have been operational since June 2004.
  - Ongoing research by UT-Austin and Texas A&M, in collaboration with local agencies is currently investigating the impact of woody plant encroachment on the hydrologic cycle at Honey Creek State Natural Area. Honey Creek is a tributary of the Guadalupe River and within the HO boundaries. This research, funded by the National Science Foundation, includes surface water and spring water monitoring, eddy covariance towers, instrumented rainfall simulation equipment, and monitored overland flow and interflow plots.

### **3 and 4. Proposed Core Data and Related Science Questions**

Core data will be collected on fluxes, stores, residence times, and flow paths according to science topics identified by CUAHSI. We detail below specific scientific topics and propose relevant data collection schemes.

### **3/4a. Sustainability of Water Resources**

Developing sustainable water resources for human and ecosystem needs is a critical issue for the proposed HO because of tight coupling between atmospheric parameters and surface and subsurface hydrology in this dynamic system. Sustainability issues include both water quantity and quality. Drought conditions are most critical for sustainability. Addressing sustainability issues requires a quantitative understanding of water availability and water needs within the context of climate variability and LULC change. The types of questions that need to be addressed include:

- Can we predict when droughts occur and how long they will last?
- How important is precipitation recycling in the basin?
- How has LULC change impacted the water cycle in the past and how is it expected to affect it in the future (increasing urbanization)?
- How does climate variability (seasonal, interannual, decadal, century, and millennia) impact groundwater recharge?
- What indicators can be used to represent overall water availability in the basin and what threshold levels can be established for human and ecosystem needs?
- What species are most vulnerable during extreme climate conditions?
- Can conjunctive use of porous media (Carrizo-Wilcox) and karst (Edwards) aquifers provide sustainable water for the region through interbasin transfers?

To address these issues we propose the following monitoring program:

- Double gage precipitation platforms to improve existing radar rainfall algorithms
- Stable isotopes of precipitation, surface water, and groundwater
- Eddy covariance and Bowen ratio flux towers, and scintillometers for ET in different LULC settings
- Soil moisture and soil water pressure sensors in different LULC settings
- Stream flow gauging upstream and downstream of recharge zone
- Drip flow monitoring in caves for groundwater recharge estimation
- Spring flow gauging for groundwater discharge
- Groundwater level recorders and electrical conductivity probes
- Biologic monitoring

These monitoring data will be used to ground-reference precipitation and ET estimates from satellite data. Increased precipitation and ET monitoring will allow us to assess precipitation recycling and positive or negative feedbacks between soil moisture, ET, and precipitation during droughts. This information is important for predicting the length of droughts and what is required to end drought conditions. Because 85% of recharge in the Edwards aquifer is derived from stream flow, additional stream flow gauging stations are required to better quantify recharge fluxes into the aquifer. The Edwards aquifer provides a unique opportunity to monitor recharge directly by measuring drip flow in caves. Unlike most other aquifers, karst systems provide a unique subsurface laboratory through the extensive network of caves in these systems. An improved understanding of potential impacts of LULC change on the water cycle can be derived from intensive monitoring of water cycle components in different LULC settings and using space as a proxy for time. Streams and springs provide critical habitat for endangered species in this region; therefore, developing regional metrics for critical low-flow conditions by relating stream and spring flow to groundwater levels and other parameters is very important for this system. Information on groundwater table fluctuations and associated salinity will be useful in evaluating relationships between drought and groundwater salinity. Reduced inflow to the system may result in the movement of saline water into the shallower groundwater

system. Biologic monitoring will be conducted to assess which species are most vulnerable to drought conditions and what their minimum water quantity and quality requirements are. Traditionally, conjunctive use refers to combined use of surface water and groundwater to improve the reliability of water resources; however, in this HO, conjunctive use could refer to combined use of karst and porous media aquifers to increase the reliability of water resources. Assessing water availability in both types of aquifers will require detailed evaluation of the groundwater budget and evaluation of optimal interbasin transfers to meet the water needs of humans and ecosystems.

### **3/4b. Linking Hydrologic and Biogeochemical Cycles**

Water is the primary vector for nutrients in the water cycle and a fundamental link for biogeochemical cycles, such as those of carbon and nitrogen. Nutrient loading, particularly nitrogen, to surface and groundwater is a critical issue for ecosystem health. Carbon cycling and vegetation dynamics can play an important role in controlling the various components of the water cycle, particularly ET. Fundamental research questions that might be addressed include:

- How does LULC change impact nutrient loading (particularly nitrogen) to the system?
- What impact does climate variability have on nutrient loading (droughts, floods)?
- What is the relative importance of point versus nonpoint sources of nutrients?
- What is the assimilative capacity of the aquifer?
- Are there thresholds for nutrient levels and soluble organic carbon levels that contribute to ecological state changes?

To address these issues we propose the following measurement and monitoring program:

- ET monitoring using eddy covariance and Bowen ratio flux towers, and scintillometers in different LULC settings
- Vegetation dynamics (biomass production, leaf area index, and CO<sub>2</sub> fluxes)
- Nitrate loading: nitrate levels in precipitation and in soils in different LULC
- Nitrate levels in streams and springs in different LULC and under different climate forcing
- Nitrogen and oxygen isotopes of nitrate and nitrogen gas measurements as indicators of denitrification in groundwater
- Biological monitoring in streams and springs with different nitrate concentrations

Monitoring ET and relating it to different LULC settings will yield valuable information on the role of vegetation in the water cycle. Well funded brush removal programs in Texas are designed to reduce ET and increase runoff and groundwater recharge. Little data are available, however, on the role of vegetation in the water cycle. Detailed monitoring of ET, vegetation dynamics, and CO<sub>2</sub> fluxes should greatly improve our understanding of linkages between hydrologic and biogeochemical cycles. This understanding should provide valuable insights into the ability of applied programs, such as brush control, to alter the water cycle and increase stream flow or groundwater recharge. Nitrate is a major contaminant in groundwater in the US. Although nitrogen levels in groundwater beneath the proposed HO are low ( $\leq 5$  mg/L NO<sub>3</sub>-N) relative to the existing maximum contaminant levels for humans (10 mg/L NO<sub>3</sub>-N), these levels may pose a threat to ecosystems in these regions. Monitoring of nitrogen and biologic systems should provide insights into threshold nitrogen levels for various species and relative vulnerability of different species. Understanding the assimilative capacity of the aquifer (N inputs relative to processes that reduce N levels, e.g. dilution, denitrification) is critical for understanding the overall N balance and the need to reduce inputs to the system to control N contamination. Newly developed N isotope techniques combined with measurement of N gas in groundwater can delineate areas of denitrification. This comprehensive approach to evaluation of the N cycle in this HO should provide a more comprehensive understanding of the N cycle and its controls.

### **3/4c. Hydrologic Extremes**

The proposed HO is highly susceptible to floods and droughts because of the tight coupling between atmospheric forcing and surface and subsurface hydrology in this system. Its close proximity to the Gulf of Mexico results in some of the most intense rainfalls in the US and flood prediction is extremely important in this system to minimize casualties and property damage. The proposed HO has also been exposed to intense droughts in the past (e.g., 1950-1957). Droughts are of particular concern for water supply and endangered species issues.

Relevant questions include:

- How can we improve flood prediction and increase the lead times?
- How reliable are estimates of high rainfall intensity in South Texas using the radar rainfall algorithm (Z-R relationship)?
- How can spatio-temporal NEXRAD rainfall be used and optimized with additional monitoring to improve flood alerts?
- What hydrologic models are most relevant to use for flood prediction?
- How can the proposed monitoring be used to reduce fatalities and property damage related to flooding?
- Is the frequency of floods and droughts related to LULC change?
- Are antecedent moisture conditions important in controlling flooding?
- What is the frequency and duration of droughts?

The proposed monitoring system would include:

- High density rainfall gauge network (in fifteen 1-km radar cells, with a set of four double gauge platforms at a given cell)
- Soil moisture monitoring in different LULC settings and soil types
- ET monitoring related to LULC
- Runoff monitoring in areas of different LULC and soil types
- A high density stream gauge network, particularly upstream of urban regions
- Groundwater level and quality monitoring adjacent to streams

The proposed monitoring system would significantly improve our ability to predict hydrologic extremes in this HO. The rain gauge network would allow adjustments (calibration and corrections) to be made to the existing radar-rainfall algorithms and thus provide improved information on spatiotemporal variability in precipitation. A new algorithm will be applied to the NEXRAD level II raw reflectivity data (1 km and 6 minutes) to derive an improved precipitation product, with additive bias-adjustment using the real time precipitation gauge network. Detailed soil moisture monitoring would allow evaluation of linkages between antecedent soil moisture and runoff and streamflow. An increased number of streamflow gauges would allow relationships between LULC settings and stream flow to be determined. High density groundwater level and quality recorders adjacent to stream gauges would improve understanding of groundwater-surface water interactions, which may be critical for maintaining minimum instream flow conditions for ecosystems. Relationships between many water balance parameters and LULC settings can be used to evaluate potential impacts of changes in LULC on the water cycle.

The monitoring data will be used in modeling analyses to develop predictive understanding of hydrologic extremes and their impacts on the water cycle. The improved spatiotemporal rainfall product will be used as input to hydrological models, such as HEC-HMS (lumped model) and Vflo<sup>TM</sup> (distributed model), to predict the peak flow and the time of the peak flow (with flood alert lead times of 2-3 hours in general from Rice/TMC system). Modeling results can then be used to issue appropriate flood warnings. In addition, to improve the alert lead time, algorithms for precipitation forecasting based on existing radar rainfall patterns (for example, the Growth and Decay Storm Tracker algorithm) will be investigated and implemented into the hydrological models.

### **3/4d. Hydrologic and Ecosystem Interactions**

The proposed HO exhibits a number of unique aspects related to interactions between hydrology and ecosystems. Large springs that emerge from the Edwards Aquifer (San Marcos Springs, Comal Springs) provide riparian habitat for 4 aquatic species listed as threatened or endangered, and have been listed as Critical Habitat. The aquifer itself also serves as a habitat for some species including the Texas Blind Salamander and 2 species of blind catfish that have been found living in the aquifer nearly 2000 feet beneath the land surface. Maintenance of spring flows in the upper portion of the watershed is critical for sustaining these endangered species and riparian habitats. The spring flows also constitute a major portion of the baseflow of the streams, which in turn provides freshwater inflows to the downstream estuary. The management of freshwater inflows to the estuary is closely related to the coupling of the river flows and groundwater from the aquifer, which sustains estuarine productivity and ecological health. Shellfish and finfish production are of special concern, as is the well-known and endangered Whooping Crane, which winters in the salt marshes of the downstream San Antonio Bay. Instream (environmental) flow management, therefore, is currently the focus of much resource planning and water law debate within Texas, including deliberations of the Texas Senate Select Water Committee and an Expert Review Panel of the National Academy of Science.

Important questions to be evaluated include:

- What critical levels of groundwater and surface waters (instream flows) must be maintained to provide needed riparian habitat for endangered species?
- How do surface water and groundwater linkages influence the biological communities?
- How do streams that go underground in portions of the watershed influence the biological communities upstream and downstream of these sites?
- How are riparian ecosystems in the watershed impacted by hydrologic extremes (floods, droughts)?
- What are the instream flow needs of ecosystems, considering the reservoirs in this watershed as integral parts of the larger river-reservoir system?
- What nutrient levels can different ecosystems tolerate without exhibiting negative biological impacts, and how can these levels be maintained?
- What best management practices and policies can be established, and in what portions of the watershed, to reduce nutrient loadings to surface water and groundwater?
- How can subsurface biota be used to provide assessment and management information on subsurface aquifer connectivity?
- What is the influence of dams on the biogeochemical cycles in the streams in the watershed?
- What is the interaction of climate variation (seasonal, interannual variation; trends with changing climatic conditions) with such factors as nutrient loadings, limitation and cycling within this river-reservoir system?

To address these issues, the following monitoring program is proposed:

- Ecosystem monitoring relative to flow regimes and nutrient levels
- Water quality and biological community monitoring above and below sites where the streams go underground, to determine how this phenomenon isolates or differentiates distinct aquatic ecosystems
- Calcium carbonate and nutrient (nitrate-nitrogen, phosphorus) concentration monitoring and interactions in reservoirs, including their role in controlling primary productivity
- Subsurface biota monitoring to obtain aquifer connectivity data.
- Ecosystem health and biological community structure monitoring in San Antonio Bay to assess effects of variable freshwater inflows

- Fish and invertebrate community monitoring in the HO watersheds in relation to differing instream flows and nutrient loadings and concentrations

The proposed monitoring program will significantly increase our understanding of hydrologic and ecosystems interactions. Monitoring ecosystems in the context of different flow regimes (floods and droughts) will be extremely important in determining threshold flows required to maintain ecosystems. This understanding will also feed into water resources management which is required to maintain minimum spring flows for endangered species. Linking nutrient levels to ecosystems will determine threshold nutrient levels and place limits on nutrient loading for ecosystem health. Understanding groundwater/surface water interactions, including impacts of reservoirs relative to ecosystems will help determine how these interactions impact aquatic ecosystems. The distribution of different subsurface biota may also be used as a tool to determine aquifer connectivity and delineate flow paths. Quantifying instream flows and associated nutrient levels from groundwater and surface water to the estuary and relating such flows to ecosystem health (fish and invertebrates) will help establish threshold levels for ecosystem health.

### **Integration of HO Components Using Numerical Modeling**

Numerical modeling will play a critical role in integrating data of different types and developing a predictive understanding of the water and related biogeochemical cycles. The monitoring program in the proposed HO will provide data input for various modeling studies and also information to evaluate model results. Modeling will be advanced from traditionally separate surface water and groundwater models to integrated atmosphere, land, and aquifer system models that will link variability in climate forcing and LULC change with the water and biogeochemical cycles. The monitoring data collected in the proposed HO will be used to provide input to a nested regional climate model for the area that can be used to address potential impacts of variability in climate and LULC change on the water cycle. Model output can also be compared with monitoring results to evaluate the validity of the simulation results. This comprehensive monitoring/modeling approach can be used to address several issues such as the following:

- Roles of vegetation heterogeneity and soil moisture variability, in central/south Texas versus sea surface temperature changes in the Gulf of Mexico and the tropical Atlantic/Pacific oceans in determining the land-ocean thermal contrast and regional moisture recycling
- Relationship between flood and drought frequencies and the variability of the Great Plains Low Level Jetstream
- Relative impact of LULC change versus climate change on precipitation patterns
- Impact of climate and LULC on groundwater recharge
- What LULC scenarios provide more or less buffer to ecological communities that share water with urban and rural areas in an area with highly variable rainfall

The scale of the HO will also allow validation of satellite-based approaches for characterizing precipitation, ET, soil moisture, vegetation dynamics, and many other parameters. The proposed Texas HO, including watersheds with very different LULC, and underlying karst and porous media aquifers, should significantly advance our understanding of the water cycle and related biogeochemical cycles in the context of variability in climate, LULC, and human and ecosystem needs.