Assessment and Value of Ecosystem Services

Preserving flows at Jacob's Well spring

Adrian L. Vogl

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SYNOPSIS

Jacob's Well is the largest perennial spring in the Trinity Aquifer and one the longest underwater caves in Texas. The cave and spring are inhabited by uniquely adapted spring and aquifer fauna. The artesian spring provides a base flow of thousands of gallons of crystal clear water per minute to form Cypress Creek and the beautiful Blue Hole swimming area. The spring also helps support a thriving ecological community in the Cypress Creek by historically providing a consistent source of fresh, clear water to the surface, even during prolonged droughts. This natural treasure is now threatened by pollution and increased groundwater pumping caused by rapid and water-intensive development in the area. Because flow at Jacob's Well is very sensitive to groundwater levels in the Middle Trinity Aquifer, the spring is the proverbial canary in the coal mine for the health of the underlying aquifer. The spring flowed through the 1950's drought of record; yet in last decade Jacob's Well has stopped flowing several times in response to much less severe droughts than were experienced in the 1950s.

Growth in the recharge and contributing areas to Jacob's Well may have significant impacts on spring flows there, but policy and planning in the area lacks a coherent framework for evaluating the impacts of such development, prioritizing areas for conservation efforts, and comparing the values derived from maintaining ecosystem services in place (such as recharge and water quality mitigation) versus the economic returns of conventional land development. The concept of ecosystem services is useful for integrating economic and ecosystem considerations into a common framework for assessing the costs and benefits of land conservation strategies. Water-related ecosystem services in the Texas Hill Country are diverse, and include water capture (infiltration), water storage (recharge), in-stream flows, channel-based aquifer recharge, and water quality protection.

An ongoing issue with incorporating the concept of ecosystem services into conservation planning is the need to define exactly what is being valued. In order to adequately assign economic values to specific ecological services, it is first necessary to quantify those services and to understand the spatial distribution of the land characteristics and uses that provide them. WVWA recently completed a comprehensive assessment of the water-related ecosystem services that support Jacob's Well spring flow and the economic value of associated lands to assist long-term planning and land conservation. This study summarizes what is known about the hydrogeology and vulnerability of Jacob Well's watersheds, but also reveals that there are still many gaps in our scientific knowledge of the aquifer system itself. The assessment of ecosystem services in the Jacob's Well area involves:

- Delineating a probable contributing area for Jacob's Well spring based on existing hydrogeologic studies
- Mapping ecosystem service provision in the probable contributing area using a combination of data collection, watershed modeling, and GIS analyses
- Developing a composite index map that demonstrates the areas with highest overall ecosystem services provision to assist in prioritizing conservation efforts
- Performing economic value assessment of water-related ecosystem services in the study area

INTRODUCTION

This study presents a framework for mapping the spatial extent of hydrology-related ecosystem services and evaluating potential economic values of these services in selected areas that are most likely to influence flow at Jacob's Well spring. For the purpose of this study we focus on the services of water capture (infiltration), water storage (recharge), in-stream flows, channel-based aquifer recharge, and water quality protection. The outputs are modeled using a combination of data compilation, mapping overlays, and watershed simulation modeling. The results of this study will 1) provide detailed spatial information on the types and magnitudes of water-related ecosystem services provided by the Cypress Creek watershed and Jacob's Well contributing area; 2) provide a basis for economic valuation of ecosystem services relating to maintaining aquifer levels and spring flows; 3) provide resource advocates with critical information to prioritize areas for ecosystem service protection.

Objectives

The objectives of the study are to:

1. Delineate probable contributing area for Jacob's Well spring for a 25-year planning horizon
2. Map ecosystem service provision in the Cypress Creek watershed and Jacob's Well contributing area
    - Develop and calibrate hydrologic model to simulate average conditions
    - Develop spatially-explicit maps of water-related ES provision, focusing on water capture and groundwater recharge, water storage, water provision to downstream reaches, and water quality protection
    - Map spatial distribution of land characteristics contributing to ecosystem services
3. Develop a composite index map that demonstrates the areas with highest overall ecosystem services provision to assist in prioritizing conservation efforts
4. Perform economic value assessment of water-related ecosystem services in the study area

METHODS

Define Jacob's Well Contributing Area

It is not possible at this time to definitely delineate the recharge area for Jacob's Well due to the high uncertainty associated with identifying and quantifying the relative contribution of preferential flow paths in the karst aquifer system. The focus in this study will be delineating a probable contributing area, with areas in close proximity to Jacob's Well being considered higher in their probability of contribution than areas farther away. For this study we adopt a 25-year conservation planning horizon, which helps to focus efforts on preserving ecosystem services in areas that will have a more immediate impact on Jacob's Well.

For this study, focus zones were determined based on a review of available literature on the hydrogeologic setting of Jacob's Well and the Middle Trinity Aquifer. Sources of information include the Hays-Trinity Groundwater Conservation District's (HTGCD) 2008 study on the hydrogeology of Jacob's Well, the Hydrogeologic Atlas of the Hill Country Trinity Aquifer (HTGCD 2010), flow gain and loss studies from TWDB and others, reported results from the TWDB Groundwater Availability Model (GAM), the Geologic Atlas of Texas, and various individual theses and reports on local hydrogeology.

Quantify and Map Ecosystem Services

Watershed modeling was performed to quantify the contribution of different land areas to diffuse groundwater recharge, water capture, and water provision within the focus zones. These contributions are modeled based on the surface characteristics of soils, topography, and current land uses. Building a high-resolution groundwater model of the Trinity Aquifer around the spring would undoubtedly be useful for increasing understanding of the local hydrogeologic system and preferential flow paths, and for assessing aquifer vulnerability in specific areas. However, collecting the necessary data at adequate resolution and building such a model from scratch was outside the scope of this project. The focus, instead, is on assessing the land surface characteristics that make some areas of higher conservation value than others based on their ability to capture, store, and recharge water in places that are likely to contribute to spring flow at Jacob's well. Conservation of open space in the study area is by definition an effort to prevent low-impact land uses from being converted to high-impact developed areas. Watershed modeling provides a way to quantify the connection between land uses, spatial connectivity, and the provision of water-related ecosystem services that sustain Jacob's Well.

For this study, the geographic scope for watershed modeling is the upper Blanco River watershed above Wimberley. The Blanco River in Hays and Blanco counties has a high likelihood of connection to the Middle Trinity Aquifer and to flow at Jacob's Well spring (HTGCD 2008). Watershed modeling of the upper Blanco River Watershed was performed using the SWAT model and the Automated Geospatial Watershed Assessment (AGWA2) software package. AGWA2 is an interface for ESRI's ArcGIS jointly developed by the U.S. Environmental Protection Agency, U.S. Department of Agriculture (USDA) Agricultural Research Service, and the University of Arizona to automate the parameterization and execution of several commonly-used hydrologic models, including SWAT (Miller *et al.*, 2007). AGWA2 uses publicly available standardized spatial datasets to develop input parameter files and display results from several watershed runoff and erosion models within a GIS framework (Miller et al. 2007).

SWAT (version 2000) is a public domain, physically-based watershed model developed by the USDA-ARS to simulate in continuous-time surface flow, infiltration, sub-surface flow, and groundwater recharge, and route these flows, sediment, and nutrients through stream channels. The model uses input with a high level of spatial detail, including information on soils, topography, land cover, rainfall, and temperature (Arnold *et al.*, 1998; Neitsch *et al.*, 2002). SWAT was developed specifically to predict the long-term impacts of land management practices and related nonpoint source pollutant loadings on water, sediment, nutrients, and agricultural chemical yields in complex watersheds with varying soils and land uses. SWAT has been used to evaluate the impacts of land use change on watershed hydrology and pollution loadings in watersheds throughout the world, including several examples in Texas (Afinowicz *et al.*, 2005; Green *et al.*, 2007; Santhi *et al.*, 2006). The 2000 version was chosen because of its stability and well-tested interface with the AGWA2 extension. Newer versions of SWAT introduce additional functionality, but algorithms for the basic simulation of hydrology such as are used in this study have not been significantly altered since the 2000 release.

Model data requirements

The AGWA2 watershed delineation and discretization tools were used to define the watershed boundary above the USGS streamflow gauge at Wimberley, and to divide the area into sub-basins and channel segments. Required input parameters are estimated as a function of topographic, soil, and land cover characteristics for each watershed response unit/sub-basin. Default parameters were taken from look-up tables provided with AGWA2 which are based on soil type, land cover, vegetative cover, etc. (Hernandez *et al.*, 2000). The SWAT model was parameterized using the SSURGO soils geodatabase from NRCS, a 10-m resolution digital elevation model from USGS, and the NLCD 2006 land cover raster. Parameterization tools in AGWA2 were used to determine initial parameter values for the model based on these datasets. Data inputs used in building and driving the SWAT model are listed below and in Table 1.

<u>Topography</u>

The National Elevation Dataset 10 meter resolution DEM available from USGS (http://ned.usgs.gov/) was used to define important topographic characteristics of the watershed such as slope, aspect, flow length, contributing areas, drainage divides, and channel networks. The DEM was pre-processed to fill sinks and smooth inconsistencies in the data.

<u>Soils</u>

Information on soil types and soil parameters is provided by the Soil Survey Geographic (SSURGO) database available from the US Department of Agriculture's Natural Resource Conservation Service (NRCS): http://SoilDataMart.nrcs.usda.gov. This data set consists of georeferenced digital map and attribute data. SSURGO is the most detailed level of soil mapping available and are digitized from maps at a 1:20,000 scale.

Land Cover

Surface characteristics such as percent cover, roughness coefficient, and sediment generation functions are calculated using land cover data for the watershed. The National Land Cover Dataset (NLCD) provides information on land cover as of 2006, in a 30 meter resolution grid format.

Climate Inputs

Observed daily rainfall and temperature data for 1995 to 2010 were used for model calibration and validation. These data were collected from six NCDC and one LCRA station (Wimberley, Fischer's Store, Blanco, Kendalia, Canyon Dam No. 3, Dripping Springs 6E, and Dripping Springs 5 SSW). The SWAT model includes a statistical weather generator, which is activated automatically by the model to fill in gaps in daily input records for climate variables. Statistics used by the SWAT weather generator include monthly averages for minimum and maximum temperature, monthly total precipitation, number of wet days, and maximum half-hour precipitation depth. These statistics can be reliably calculated from nearby weather stations with long meteorological records, even if small gaps in the records exist.

Hydrology

Daily mean streamflow data were collected from the Blanco River at Wimberley gauge (USGS #08171000). The period of 1995 to 2010 was used for calibration and validation of the SWAT model.

Table 1. Data Required for Development of SWAT model

Type of Measurement or Analysis	Type of Data	Units	Source	Use
Topography	10-m resolution digital elevation model (DEM)	GIS coverage	USGS http://ned.usgs.gov/	Define the watershed's geographic and topographic characteristics for SWAT model
Soils	SSURGO database	GIS shapefile + database	USDA NRCS http://SoilDataMart.nrcs.usda.gov	Define soils-related parameters for SWAT model
Land Cover (2006)	National Land Cover Dataset classification	GIS coverage	MRLC http://www.mrlc.gov/finddata.php	Define vegetation-related parameters for SWAT model
Climate	Daily weather data (rainfall, min. and max. air temperature	in, °C, etc.	NCDC and NWS websites on NOAA http://www7.ncdc.noaa.gov/CDO/cdo	Input data to SWAT
Hydrology	Daily mean spring flow, Jacob's Well	cfs	USGS gage 08170990 http://waterdata.usgs.gov/nwis	Input data to SWAT
Hydrology	Daily mean streamflow, Blanco River at Wimberley	cfs	USGS gage 08171000 http://waterdata.usgs.gov/nwis	Calibrate and validate SWAT model

Calibration

Model calibration is the process where the model input parameters are adjusted until the simulated data from the model match with observed data. The period 1995-2002 was used for calibration, and 2003-2010 used for model validation. For this study, the focus of model calibration was on achieving a reasonable approximation of the overall daily flow regime and reasonable estimates of annual mean flow. Daily mean flows from the USGS gauge on the Blanco River at Wimberley were used to compare with model outputs and to determine if this criterion was adequately met. Qualitative comparisons of simulated and observed daily flow time series and flow duration curves were also used to evaluate model performance and to ensure a reasonable approximation of the overall flow regime.

Calibration of simulated annual flow volumes involves changing the most sensitive model parameters relating to rainfall-runoff partitioning, infiltration and groundwater return flows, based on information provided in the SWAT documentation (Neitsch *et al.*, 2002). The most sensitive parameter in SWAT is the curve number, which is estimated as a function of hydrologic group, hydrologic condition, cover type, and antecedent moisture condition, based on look-up tables provided with the AGWA2 package. Curve number multipliers were applied by land cover category rather than by sub-basin, to calibrate the weighted average curve number by sub-basin while preserving the model's sensitivity to changes in land cover for scenario evaluation. There was an assumption that the integrated hydrologic response of an area, as represented by the curve number, would show more variability between watersheds for undeveloped land cover types (forest, shrub, grassland, etc.) than for developed ones. As development density and impervious cover increase, the influence of local soil and vegetation conditions become less important and runoff from these areas is consistently much higher than for undeveloped areas with high vegetative covers (Brabec *et al.*, 2002; Corbett *et al.*, 1997; Whitford *et al.*, 2001). For this reason, multipliers applied to curve numbers during calibration were of larger magnitude for undeveloped land classes than for developed ones.

Model Validation

The SWAT model is built with state-of-the-art components in an attempt to simulate a wide range of watershed processes physically and realistically. Most of the model inputs are physically based (that is, based on readily available information or upon mechanistic relationships). SWAT is not a simple "one-parameter model" which can be implemented in a formal optimization procedure (i.e. in the calibration process) to fit any set of data. Instead, there are a number of input variables that are not well defined physically, including the runoff curve number (CN2) and the management and cover factor (C Factor) in the Universal Soil Loss Equation. While these model parameters may be adjusted within literature values so that the results are consistent with knowledge of watershed processes, there is no unique solution to the validation process because there are generally many more free parameters than available field data for validation.

Validation of the SWAT model was conducted for the period 2002 to 2010, a different long-term record than used in the calibration process. In the validation process, the model is operated with input parameters set during the calibration process without any change and the results are compared to the remaining observed data to evaluate the model predictions. The same evaluation measures from the calibration process are used for assessing the performance of the model during validation. If evaluation measures do not indicate valid model results, the calibration process is revisited until a best fit between simulated and observed data is obtained for both calibration and validation periods.

Model Application

The calibrated and validated watershed model was used, along with the statistical weather generator, to simulate average annual conditions over a period of 15 years. Average annual water yield, groundwater recharge, and surface runoff were computed for both historical and dry climate conditions, using results from simulations run using a Monte Carlo method. Monte Carlo simulations were conducted using the SWAT weather generator by varying the random number seed cycle code used by the model to generate daily weather inputs. A total of 200 model runs were performed and annual average values compiled for each channel segment and sub-watershed.

Baseline weather statistics (used to represent historical conditions) were computed from the Blanco weather station with an 86 year period of record. To address the potential for extended drought or future climate change, Monte Carlo simulations were also run and averaged using the statistical weather generator with parameters altered to represent a drier climate, consistent with results from the Canadian Climate Center Model (CCC; Felzer and Heard, 1999). The CCC model results were chosen to represent decreasing rainfall conditions, as they predict an average decrease in rainfall over the study area by 10%. Global climate models generally agree that Texas will experience an increase in extreme weather events, so the maximum half-hour rainfall total was increased 15% and the number of wet days per month was decreased by 15%. This has the effect of increasing the intensity of storm events while simulating those events on fewer days of the month, increasing the average dry period length while decreasing overall precipitation totals.

Spatial Assessment of Ecosystem Services

In addition to the watershed modeling described above, additional data sources were compiled to help define the contribution of individual land parcels to preservation of water-related ecosystem services and the maintenance of the Trinity Aquifer that feeds Jacob's Well spring. The unit of analysis for this assessment was the individual land parcel. Land parcel data as of 2010 were obtained from property appraisal districts in Hays, Blanco, Comal, and Kendall counties. Once the focus areas were determined, land parcel data layers were clipped to the outline of the study area and so for the final analysis include only parcels in Hays, Blanco, and northern Comal counties.

Criteria were developed to assess the ecosystem service value of individual parcels based on a review of available literature, TWDB GAM model results, and aquifer vulnerability assessments. Criteria considered in this study include:

- Focus zones based on physical characteristics and literature review of hydrogeologic studies (as described in *Define Jacob's Well Contributing Area*, above)
- Proximity to mapped cave passages of Jacob's Well
- Existence of known karst features or having the right lithology where karst development is likely
- Simulated average annual groundwater recharge
- Proximity to riparian zones
- Protected status
- Proximity to protected areas or large open spaces

Synthesis

Spatial data layers resulting from the above analyses were compiled to develop a composite map that gives a relative score for each land parcel. The relative score represents the composite contribution to ecosystem services that support Jacob's Well spring flow. The composite score is based on the criteria and scores listed in Table 2. Scores are assigned to each parcel based on its location relative to the feature or area of interest. The scores for each parcel are averaged together, and the resulting index score used to represent the overall conservation value of a given parcel. The linear averaging scheme was chosen because it is straightforward, does not prioritize some criteria over others, and therefore allows flexibility for further analyses based on a subset of criteria if desired.

Table 2. Criteria for composite ecosystem services scores

Criteria	Description	Scores
EcoServ Zone	Focus Zones based on physical characteristics and literature review hydrogeologic studies	0 = Out of focus zones 1 = Zone 1 (Cypress Creek watershed above JW) 2 = Zone 2 (portions of Blanco River watershed)
CavePassages	Proximity to mapped cave passages feeding Jacob's Well	0 = Away from cave passages 1 = Within 500 m upgradient from known passages
Kgr_L_	Existence of outcrops of the Lower Glen Rose, Cow Creek, or Hensell Sand karst	0 = No karst geology 1 = Karst geology

	formations	
KarstFeature	Mapped karst feature present	0 = No karst features 1 = Known karst features
AvgRchScore	Average annual groundwater recharge	0 to 1 based on equal intervals: 0 0 in 0.2 0.001 – 1.2 in 0.4 1.2 – 2.4 in 0.6 2.4 – 3.6 in 0.8 3.6 – 4.8 in 1 4.8 – 6.0 in
Riparian	Proximity to riparian areas/stream channels (within 50 m)	0 = Outside riparian area 1 = Within 50 m of riparian area or stream channel
ProtectedStatus	Land protection in place (public land, parks, conservation easements, etc.)	0 = Protected 1 = Not protected
ProximityOpenSpace	Proximity to protected areas and/or large undeveloped spaces	

RESULTS

Jacob's Well contributing area

It is not possible at this time to accurately delineate the recharge area for Jacob's Well due to the high uncertainty associated with identifying and quantifying the relative contribution of preferential flow paths in the karst aquifer system. The focus in this study was to delineate a probable contributing area for the purpose of conservation planning with a 25-year horizon. A study done by the Hays-Trinity Groundwater Conservation District in 2008 concluded that the source of rapid-response flow in Jacob's Well during storm events is roughly equivalent to the Cypress Creek watershed. The watershed boundary encompasses an outcrop of the Lower Glen Rose formation, which acts as an unconfined aquifer in that area. Karst development in the Lower Glen Rose allows rapid recharge and through-flow and likely contributes to the rapid storm response at Jacob's Well. In addition, the importance of water conservation measures relating to groundwater extraction in the watershed cannot be overstated. Water intercepted here to provide domestic or public water supply will continue to impact local groundwater levels and also the many seeps and springs in the area, including Jacob's Well. Evidence from pump tests at two nearby water supply wells have confirmed the connection between pumping rate and flow rate measured at the spring.

It is unlikely, however, that recharge within the Cypress Creek watershed contributes significantly to base flow. Groundwater under artesian conditions in the Cow Creek formation provides the majority, if not all of the base flow at Jacob's Well. Groundwater flow in the Middle Trinity is roughly northwest to southeast, traveling through Blanco and Hays Counties before passing through the miles of mapped cave passages to the north and west of the spring. The major source of recharge to the Cow Creek occurs west of the Cypress Creek watershed from the downward leakage of water from the Upper and Lower Glen Rose and Hensel where these formations are exposed at the surface and exposed to precipitation (near Hays-Blanco county line). There is some evidence that flow in the Blanco River may contribute to Jacob's Well under certain flow conditions, as water passes through the series of faults that run generally southwest to northeast from the Blanco River to the Cypress Creek.

Over long time scales, it is possible that recharge to the Middle Trinity also occurs through outcrops of the Hensell Sand formation along the Pedernales River. This area may provide direct recharge to the confined portion of the Middle Trinity, making preservation of open space and water yields in the upper Pedernales watershed a priority for maintaining the aquifer levels. However a direct connection between recharge in that area and discharge from Jacob's Well spring has not been established. There are many miles of unregulated domestic wells in between, making it difficult or impossible to accurately estimate the benefits to Jacob's Well spring that would result from land conservation in the Pedernales River watershed. For short-term planning, it is recommended that the focus of conservation efforts remain in areas with a higher probability of direct connection to the Trinity Aquifer and Jacob's Well, particularly areas in close proximity (such as within the Cypress Creek watershed). This helps to ensure that well development would be less likely to capture the water that would otherwise be saved through conservation efforts.

Given the above evidence, the focus area chosen for the ecosystem services inventory is primarily the Upper Blanco River and Cypress Creek watersheds. That area is the most likely source of recharge to both confined and unconfined flow components of the spring. Over longer time scales, recharge may occur in other upgradient areas in Hays and Blanco counties and along surface outcrops of formations that comprise the Middle Trinity aquifer (Lower Glen Rose, Hensell Sand, and Cow Creek). Potentiometric maps resulting from TWDB's GAM model show drawdowns in the Middle Trinity around pumping centers near the City of Blanco, drawdowns of 15 to 20 feet under Scenario 6. The results show another area of depression to the east of Blanco, associated with the study area and Jacob's Well spring. Therefore the focus area was delineated to exclude areas to the west of the City of Blanco, because water produced in these areas is not likely to augment aquifer levels or groundwater flow towards Jacob's Well, rather it is more likely to get discharged via supply wells in major pumping centers before reaching the spring.

The map below shows the general study area, which encompasses western Hays county, Blanco county, and part of Comal county. Given the average daily mean flow for the period of record (7.25 cfs) and estimates of average annual recharge given in HTGCD 2008, the amount of land area needed to produce the flow at Jacob's Well would be over 6,700 km^2. The area encompassed in the general study area is only 1,935 km^2. This is for two main reasons: 1) because of the relative importance of direct recharge through surficial karst features, it is likely that recharge is highly spatially variable. Therefore the actual land area needed to provide flow to Jacob's Well could be somewhat less than estimated; and 2) groundwater conservation efforts in the study area are limited by the dual problems of exempt domestic wells and the lack of attention to conservation goals when planning for new water supply wells. Therefore, as you move farther away from the discharge point (Jacob's Well spring), the likelihood is reduced that the water produced from conserved lands would not be intercepted before augmenting spring flows. Therefore we recommend two focus areas for conservation efforts:

- The Cypress Creek watershed (Zone 1), where high growth is planned and new supply wells that divert groundwater flow from the spring are likely. This area is also critical for maintaining water quality in the spring, the lower Cypress Creek, and Jacob's Well Natural Area as well as wildlife habitat.
- The Upper Blanco River watershed east of Blanco and the Little Blanco River watershed (Zone 2). This zone includes losing stretches of the Blanco River and produces water that flows over the fault zone south of Jacob's Well. These losses from the Blanco River through the fault system may be a source for recharge to the spring and the Middle Trinity aquifer under certain flow conditions.

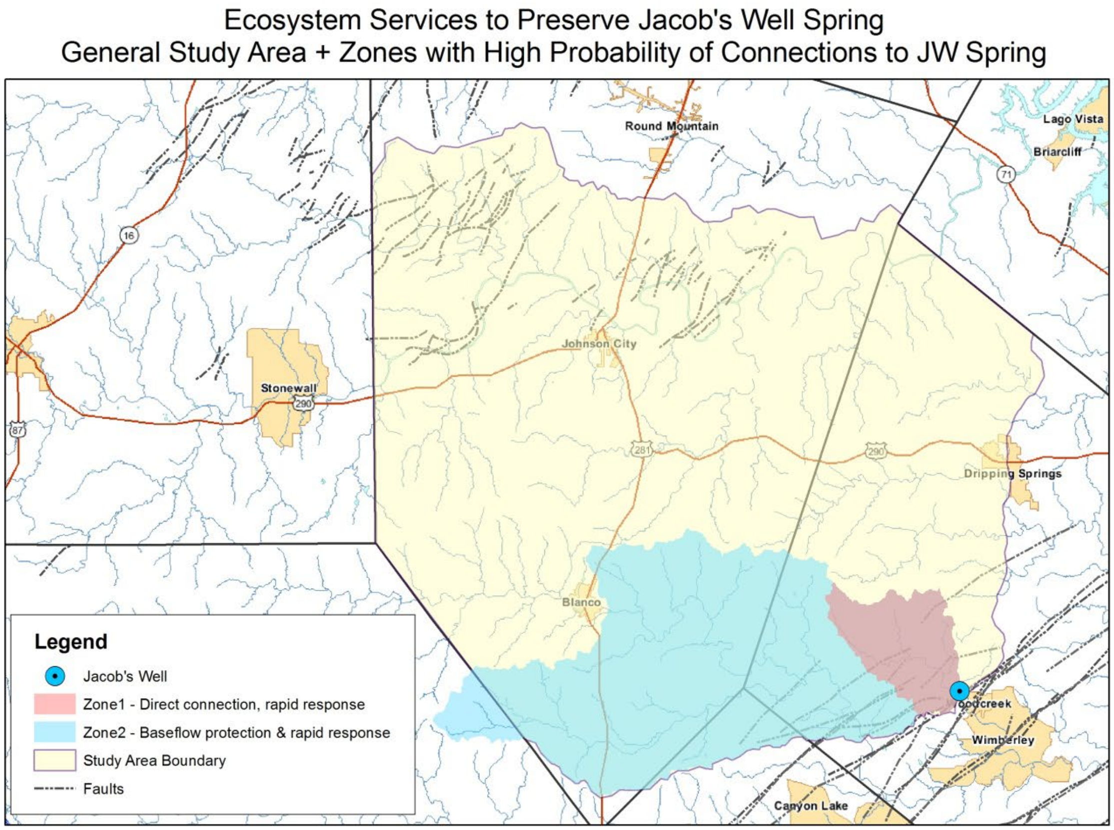


Figure 1. General study area and focus zones for ecosystem services assessment.

Quantify and Map Ecosystem Services

The Middle Trinity Aquifer directly underlies the Upper Trinity Aquifer in the study area, and consists of the Lower Glen Rose, Hensel, and Cow Creek formations. Where exposed on the surface, particularly in the Woodcreek area along Dry Cypress Creek, the Lower Glen Rose has faults, fractures and karst features which allow for rapid and significant recharge of precipitation runoff. The many direct pathways to the subsurface enhance local recharge and limit the amount of runoff into dry Cypress Creek. Springflow from Jacob's Well consists of artesian flow from the Cow Creek formation flowing up through the confining Hensel and Lower Glen Rose. The major source of recharge to the Cow Creek occurs west of the Cypress Creek watershed from the downward leakage of water from the Upper and Lower Glen Rose and Hensel where these formations are exposed at the surface and receptive to the infiltration of precipitation. Direct recharge from precipitation occurs in up dip areas where the Cow Creek is exposed at the surface in Blanco County (along the Pedernales River). Within the study area, the Cow Creek is exposed beneath and along the banks of the Blanco River near Valley View Road. Flow in the Blanco River may also provide recharge to the Cow Creek in this area. Water moves downward into the Cow Creek and down dip (southeastward) towards the Balcones Fault Zone. These karst formations and surface outcrops are critical for capturing water and directing flow into the aquifer and Jacob's Well spring.

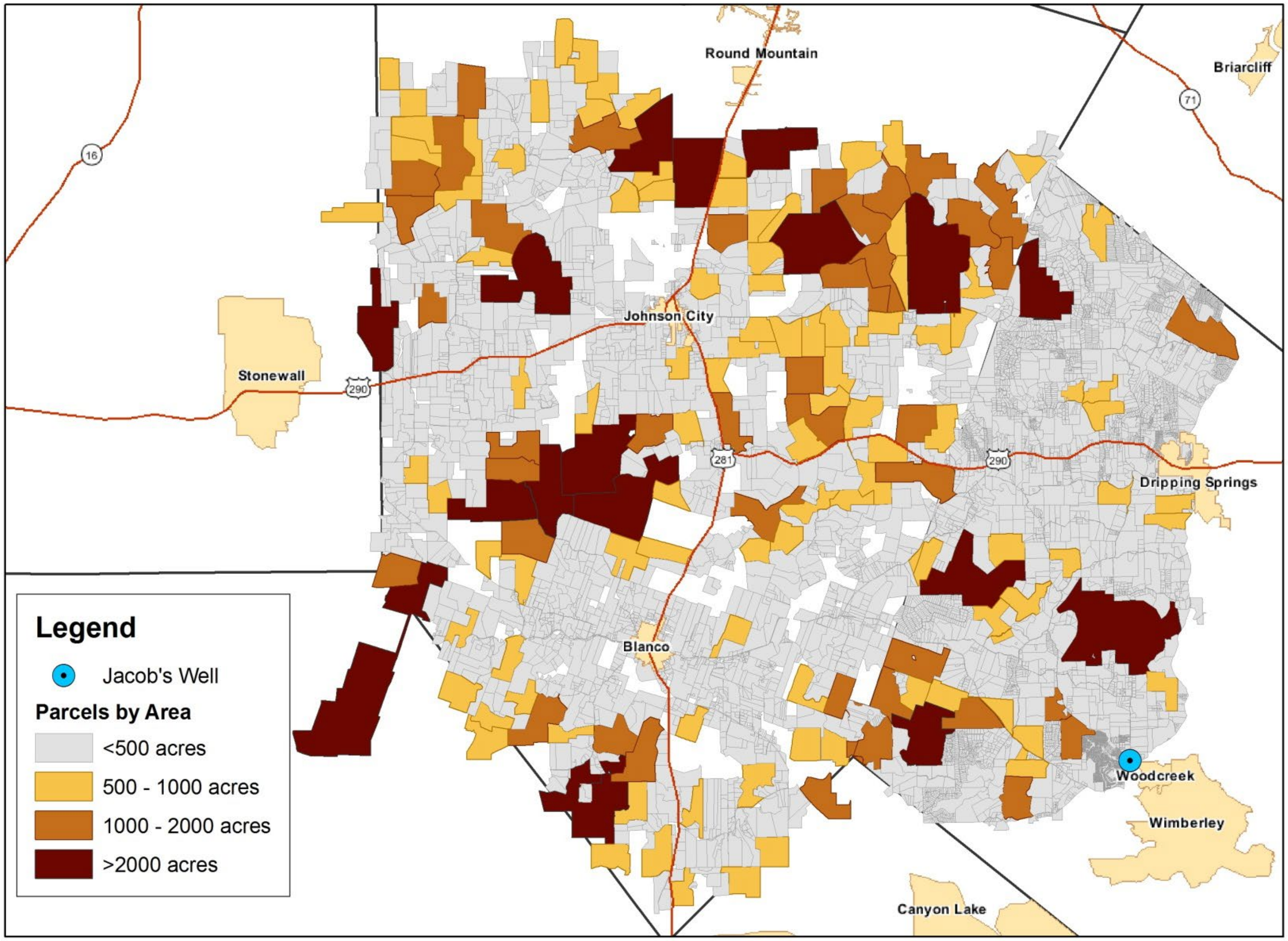
Many karst features have been mapped throughout the study area, and these are often associated with karst formations. Many such features have been mapped where the Lower Glen Rose outcrops in the Cypress Creek watershed. However it is not possible to determine the extent of unmapped karst features that exists in the entire study area. Because of the importance of surface outcrops of Lower Glen Rose, Hensell Sand, and Cow Creek formations for recharge to the Middle Trinity and Jacob's Well, it is possible to identify properties that are very likely to contain karst features or contribute to recharge based on their surface geology. Figure 3 below shows the extent of Lower Glen Rose outcrops in southern Hays County. Figure 4 identifies parcels that are located along such outcrops, plus parcels that contain known (mapped) karst features such as caves, seeps, and springs.

Other criteria considered in the assessment of ecosystem services maps include:

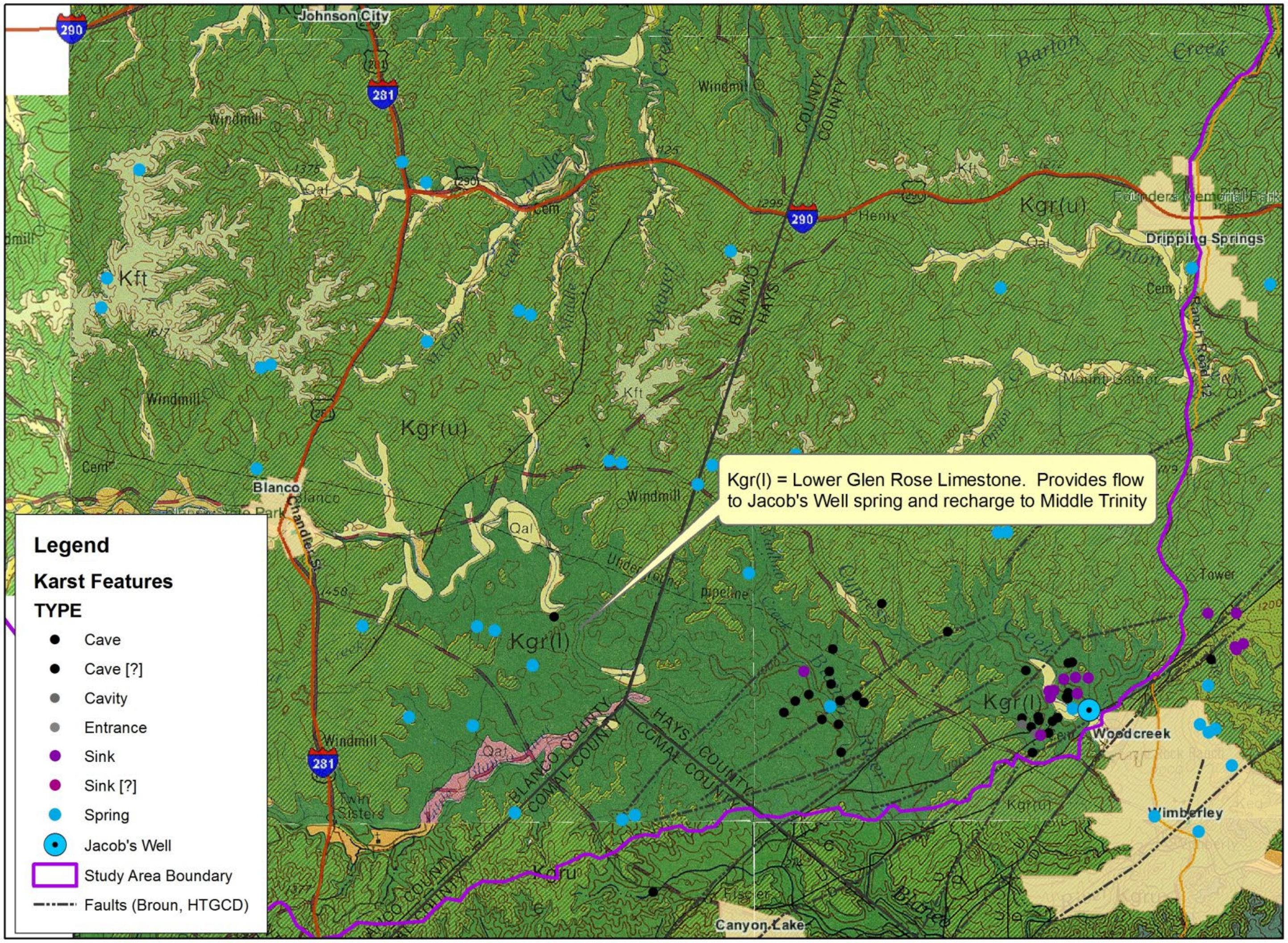
- Simulated average annual groundwater recharge
- Proximity to riparian zones
- Protected status (conservation easement or other protection in place)
- Proximity to protected areas or other large open spaces

Figures 5, 6, and 7 show results from watershed modeling under historical climate conditions and other criteria considered critical for ecosystem services to Jacob's Well spring.

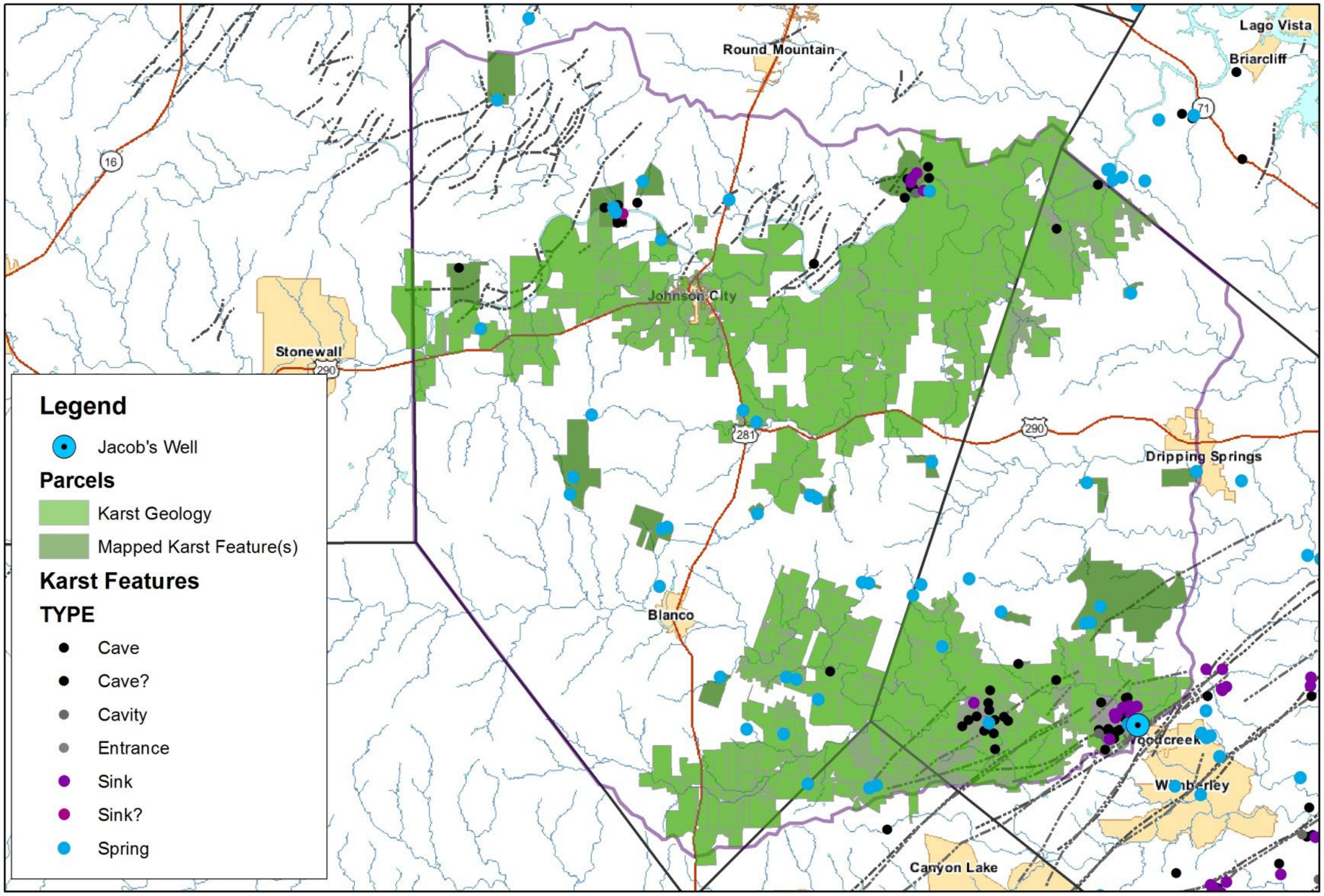
Parcels by Area



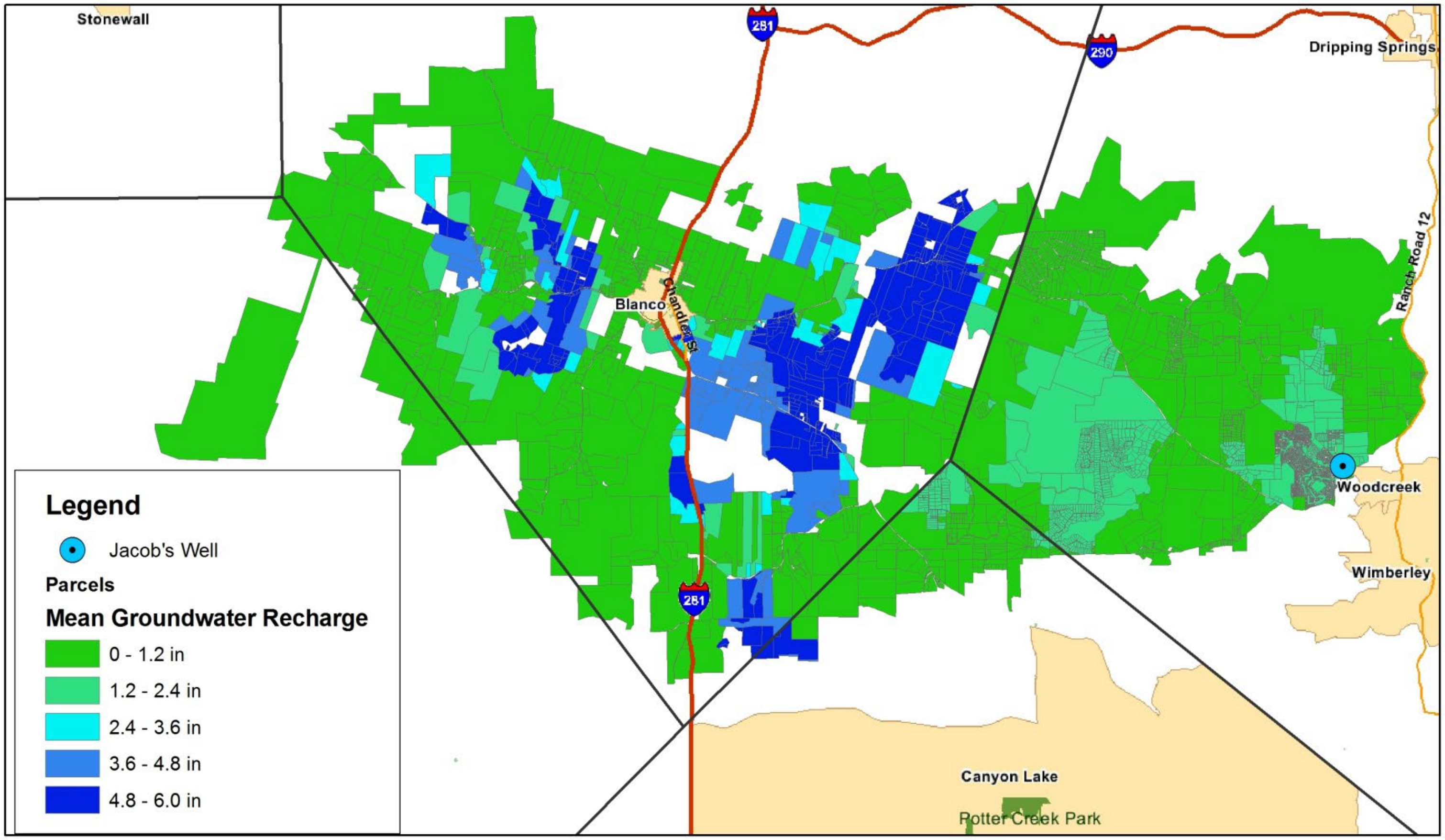
Karst Geology and Identified Karst Features



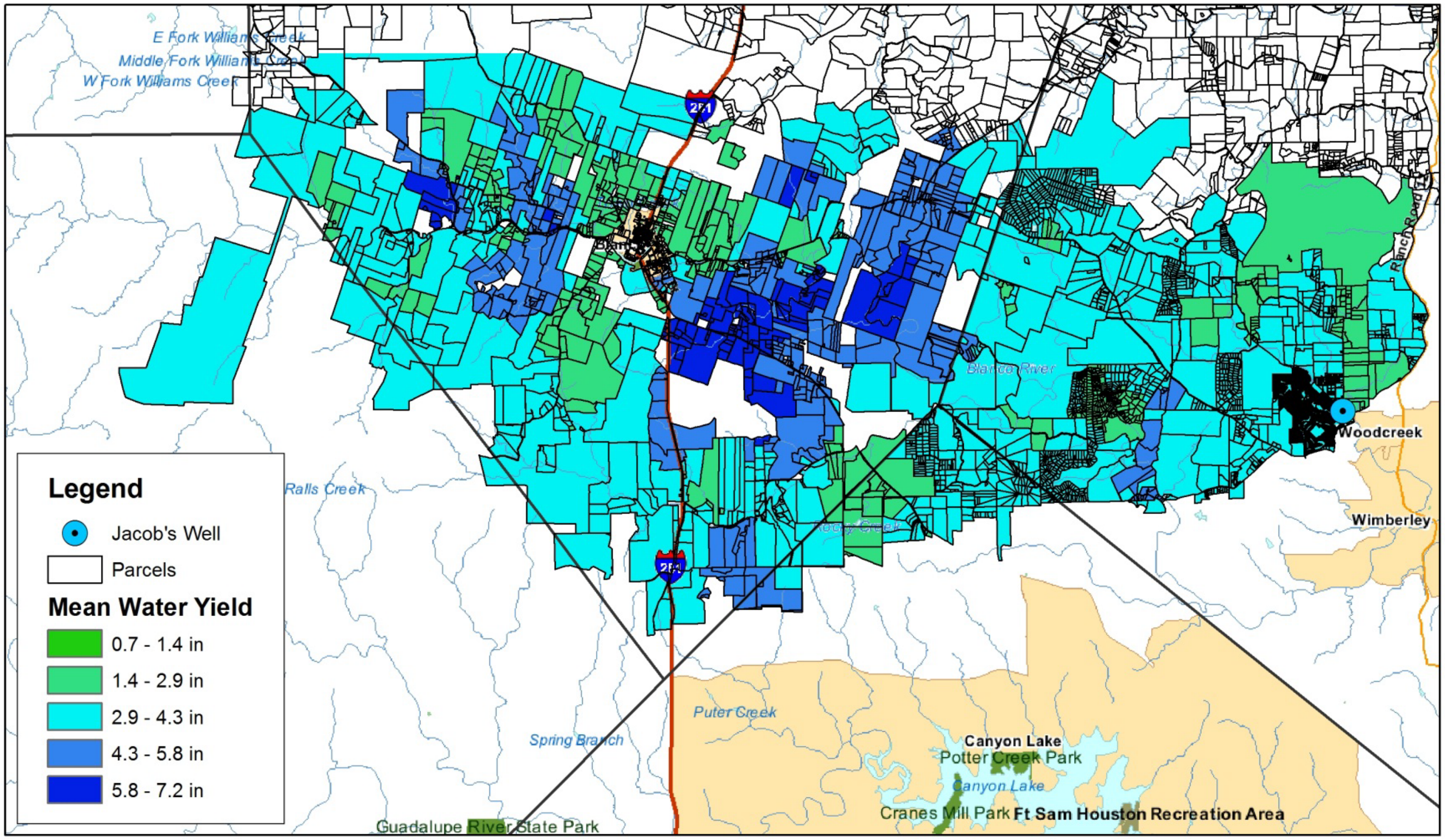
Parcels with Karst Geology and/or Mapped Karst Features



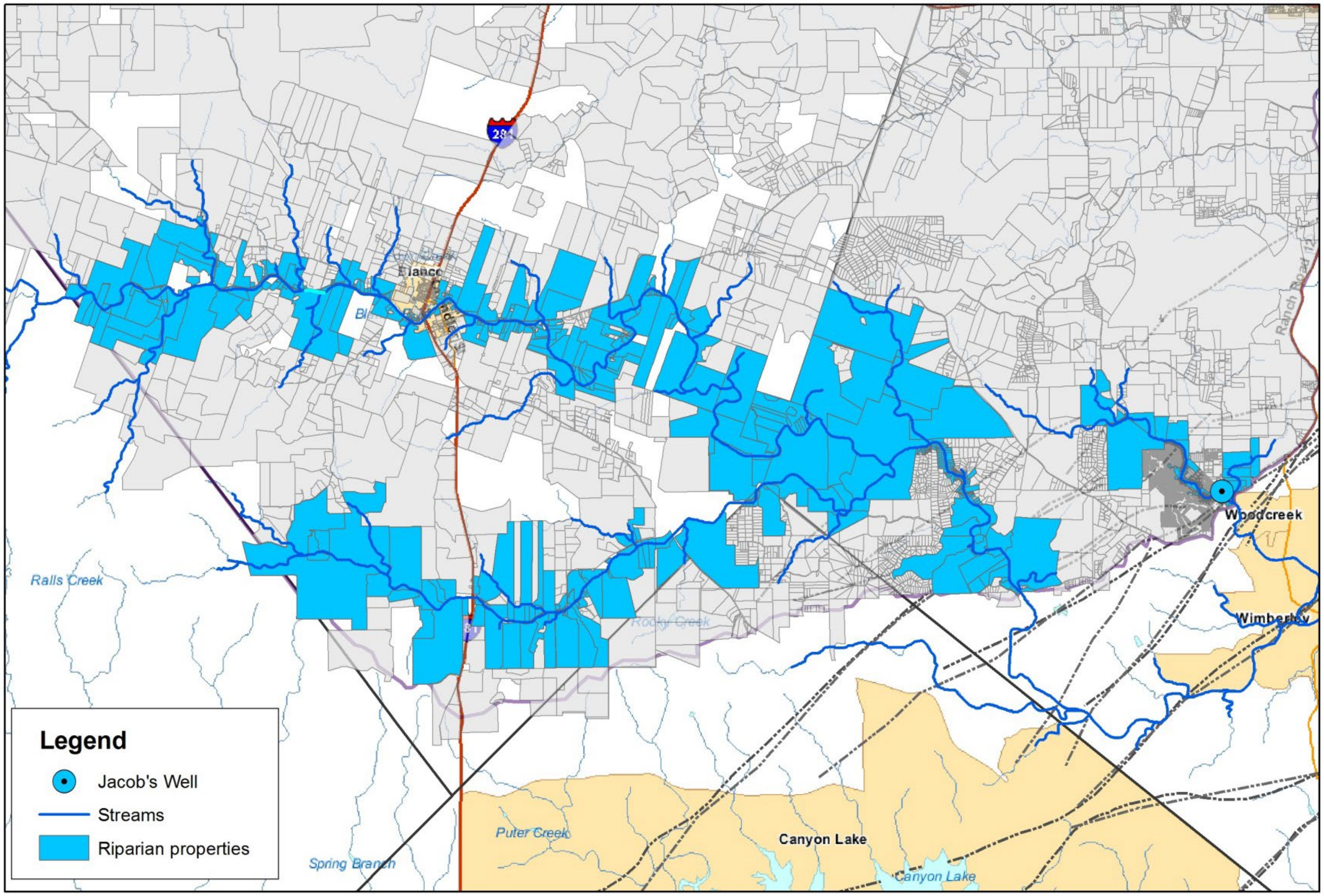
Average Annual Groundwater Recharge
Source: Upper Blanco River SWAT model



Average Annual Water Yield
Source: Upper Blanco River SWAT model



Riparian Parcels



SYNTHESIS

It is not possible at this time to accurately delineate the recharge area for Jacob's Well due to the high uncertainty associated with identifying and quantifying the relative contribution of preferential flow paths in the karst aquifer system. The focus in this study was to delineate a probable contributing area for the purpose of conservation planning with a 25-year horizon. A study done by the Hays-Trinity Groundwater Conservation District in 2008 concluded that the source of rapid-response flow in Jacob's Well during storm events is roughly equivalent to the Cypress Creek watershed. In addition, the importance of water conservation measures relating to groundwater extraction in the watershed cannot be overstated. Water intercepted here to provide domestic or public water supply will continue to impact local groundwater levels and also the many seeps and springs in the area, including Jacob's Well.

Groundwater under artesian conditions in the Cow Creek formation provides the majority, if not all of the base flow at Jacob's Well. Groundwater flow in the Middle Trinity is roughly northwest to southeast, traveling through Blanco and Hays Counties before passing through the miles of mapped cave passages to the north and west of the spring. The major source of recharge to the Cow Creek occurs west of the Cypress Creek watershed from the downward leakage of water from the Upper and Lower Glen Rose and Hensel where these formations are exposed at the surface and exposed to precipitation (near Hays-Blanco county line). There is some evidence that flow in the Blanco River may contribute to Jacob's Well under certain flow conditions, as water passes through the series of faults that run generally southwest to northeast from the Blanco River to the Cypress Creek.

Over long time scales, it is possible that recharge to the Middle Trinity also occurs through outcrops of the Hensell Sand formation along the Pedernales River. This area may provide direct recharge to the confined portion of the Middle Trinity, making preservation of open space and water yields in the upper Pedernales watershed a priority for maintaining the aquifer levels. However a direct connection between recharge in that area and discharge from Jacob's Well spring has not been established. There are many miles of unregulated domestic wells in between, making it difficult or impossible to accurately estimate the benefits to Jacob's Well spring that would result from land conservation in the Pedernales River watershed. For short-term planning, it is recommended that the focus of conservation efforts remain in areas with a higher probability of direct connection to the Trinity Aquifer and Jacob's Well, particularly areas in close proximity (such as within the Cypress Creek watershed). This helps to ensure that well development would be less likely to capture the water that would otherwise be saved through conservation efforts. The focus zones shown in Figure 1 were determined to be the most valuable conservation areas for protecting Jacob's Well spring, based on current understanding of the aquifer system and the hydrogeologic setting.

In addition to the delineating the probable recharge area, additional data sources were compiled to help define the contribution of different land uses to preservation of water-related ecosystem services and maintenance of the Trinity Aquifer in the study area. Criteria used in the development of composite ecosystem services maps include:

- Location within the probable contributing areas as described above
- Proximity to mapped cave passages of Jacob's Well
- Existence of known karst features or having the right lithology where karst development is likely
- Simulated average annual groundwater recharge
- Proximity to riparian zones
- Protected status (conservation easement or other protection in place)
- Proximity to protected areas or other large open spaces

Results from modeling and data collection consistently reveal an area in eastern Blanco county along losing segments of the Blanco River, as well as the Cypress Creek watershed itself, as critical zones for protecting recharge, rapid-response flow and water quality in Jacob's Well. Jacob's Well spring represents a key resource in connecting people to the environment and ensuring they understand the interdependencies between the community and the supporting ecosystems. WVWA will continue to support additional data collection and scientific studies through our partnering organizations to further refine our understanding of the hydrogeology of Jacob's Well spring, and to more accurately define the boundaries of the geographic area that contributes to recharge and the maintenance of flow in the spring and in the Cypress Creek. Future work needed in this area includes using the results of the ecosystem services assessment, in conjunction with regional conservation partners, to develop a conservation plan and implementation strategy that will address long-term land conservation needs in the Wimberley Valley and the Hill Country. WVWA will continue to support the creation of a Special Groundwater Management Zone for the Jacob's Well catchment area, and will use the results from its ecosystem services assessment to help define the geographic boundary and management needs associated with such a zone.