Hydrogeological Assessment of Aquifer Storage and Recovery and Aquifer Recharge Suitability within Prairielands GCD

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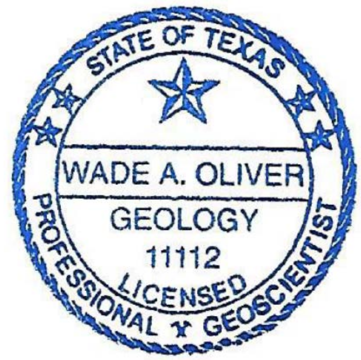

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ACROYNMS AND ABBREVIATIONS

GCD	Groundwater Conservation District
ASR	Aquifer Storage and Recovery
AR	Aquifer Recharge
LID	Low Impact Development
TDS	Total Dissolved Solids
NTGAM	Northern Trinity Groundwater Availability Model
SSUGRO	Soil Survey Geographic Database
USDA	United States Department of Agriculture
TCEQ	Texas Commission on Environmental Quality
NOAA	National Oceanic and Atmospheric Administration
DEM	Digital Elevation Model
ft	feet

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1.0 BACKGROUND

During the past decade in Texas there have been multiple years of extreme drought and extended periods of above normal temperatures, which have consequently decreased inflows to surface water reservoirs and increased evaporative losses from surface water reservoirs. This increased water stress has driven a need for more water storage in many areas of Texas, but the time required to plan, permit, design, and construct new surface water reservoirs can be in the range of 25-30 years. Given the near-term water supply demands there has been increased interest in managed aquifer recharge (MAR) techniques that can increase the quantity and quality of groundwater available in the near-term. There are two general types of MAR, aquifer storage and recovery (ASR) and aquifer recharge (AR) sometimes referred to as artificial recharge. These two types of MAR will be described below.

The potential benefits that ASR and AR methods may provide have prompted several bills in the last wo legislative sessions. In 2018, the Texas 86th Legislature passed three bills aimed at encouraging further development and use of ASR and AR projects. HB 721 directs the TWDB to conduct studies on ASR and AR projects in the State Water Plan and required the TWDB to conduct a survey to identify the relative suitability to various aquifer for use in ASR and AR projects (Shaw and Others, 2020). The statewide study suggests there are large swaths of the District that are considered "most suitable" for both ASR and AR. However, these suitability rankings were evaluated on a grid with a resolution of 50,000 feet x 50,000 feet (or 89.5 square miles), which is too coarse to evaluate the feasibility of ASR/AR strategies at the District level. The primary objective of this study was to refine the techniques used in the statewide TWDB study to achieve a better geographic resolution.

1.1 Aquifer Storage and Recovery

The Texas Water Development Board (TWDB, 2018) defines aquifer storage and recovery (ASR) as "the storage of water in a suitable aquifer through a well during times when water is available, and the recovery of water from the same aquifer during times when it is needed." ASR facilities have been increasingly recognized as a viable option to help communities and industries in Texas address water supply needs. When comparing ASR systems to surface water reservoirs, there are several key benefits:

- No water loss to evaporation
- No surface inundation with its associated condemnation, environmental impacts, and years of permitting/regulatory issues
- No loss of storage capacity due to sedimentation
- Scalability, capital costs start at 1-2 million, rather than 10s to 100s of millions.

A review of existing ASR projects nationally documents the following ASR objectives and benefits: added seasonal storage, increased long term storage (banking), increased emergency storage/supply, ability to defer expansion of water facilities, enhance environmental flows/ecosystem maintenance, restoration of groundwater levels, and subsidence mitigation (Bloetscher and others, 2014). Through creation of storage, ASR and AR are ideal for increasing water availability through the use of surface and groundwater.

Within the District there has been only one preliminary assessment of an ASR project in Johnson County, which would utilize excess capacity from Lake Granbury Surface Water Advanced Treatment System when available (detailed in Region G Regional Water Plan). To the north in Tarrant County there have been countywide and stie specific studies focused on investigating the feasibility of ASR systems (CDM 2000, 2002 and CDM and INTERA 2014). These studies identified potentially suitable areas for ASR throughout Tarrant County and found site specific locations where ASR could be sourced from reclaimed water from co-located water treatment facilities.

1.2 Aquifer Recharge

Aquifer recharge techniques, as defined by HB 721 and amended Section 11.155 of the Texas Water Code, "involves the intentional recharge of an aquifer by means of an injection well authorized under Chapter 27 of the Texas Water Code or other means of infiltration, including actions designed to (a) reduce declines in the water level of the aquifer; (b) supplement the quantity of groundwater available; (c) improve water quality in an aquifer; (d) improve spring flows and other interactions between groundwater and surface water; and (e) mitigate subsidence. The key difference between ASR and AR as defined in the Texas Water Code is in ASR there is intent to recover recharged water, while in AR there is no specific intent to recover recharged water.

There are many possible aquifer recharge strategies that fall under "other means of infiltration," such as enhanced surface infiltration and vadose zone well infiltration. The TWDB defines enhanced surface infiltration as a process that involves holding water above a pervious land surface for a longer period than would occur naturally so that water can percolate into the underlying aquifer(s). This can be accomplished with engineered spreading basins, diversions of excess surface water to fallowed fields, and by impeding natural water courses. Enhanced surface infiltration projects are also scalable in terms of cost and quantities of water infiltrated. Figure 1-1 shows four common aquifer recharge strategies and literature estimates of potential annual recharge volumes. Annual estimates vary widely because of recharge volumes depend on hydrogeologic conditions, availability of source water, and project design. Currently, there are numerous examples throughout the United States and internationally of successful implementation of enhanced infiltration projects (Stefan and Ansems, 2017). In Texas, El Paso Water Utilities uses spreading basins successfully to recharge the Hueco Bolson Aquifer with reclaimed water (Malcom Pirnie, 2011).

In urban environments, where land availability, land procurement costs, and permitting essentially prohibit larger footprint recharge strategies, low-impact development strategies (LID) have been developed. LID systems are often developed at a relatively small scale (e.g., pervious pavement along the edge of streets, or vegetated swales to collect runoff from parking lots), close to the source of runoff generation, with the goal of slowing the movement of water across the landscape. One of the most commonly used LID systems is stormwater collection linked to a vadose zone well. Vadose zone wells are relatively shallow, large-diameter wells, completed above the water table, that facilitate infiltration. Water can be diverted to these vadose zone wells where it is allowed to seep into the subsurface under the force of gravity.

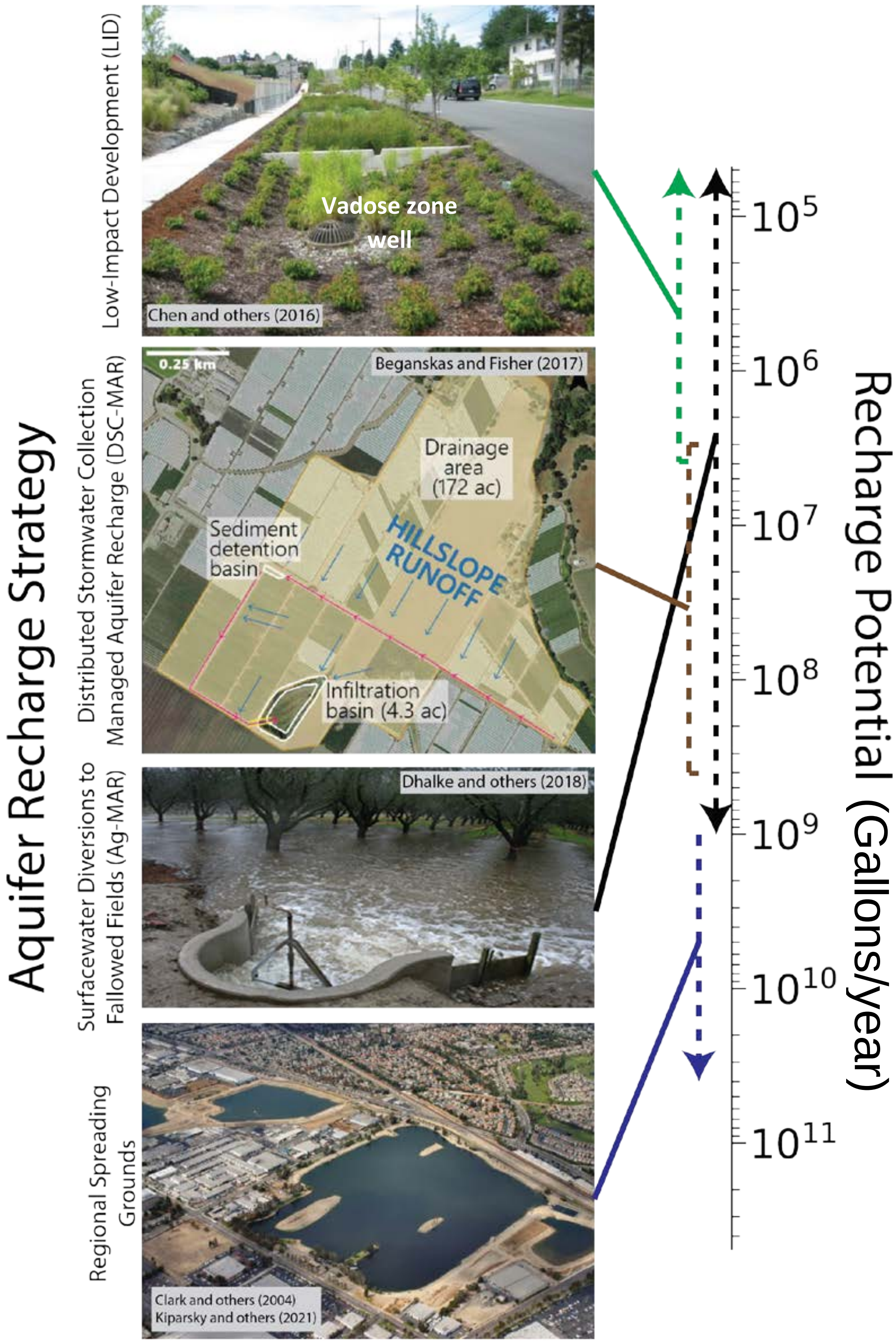

Figure 1-1 Aquifer Recharge (AR) strategies and potential recharge volumes (gallons/year) associated with each strategy.

2.0 DISTRICT HYDROGEOLOY

Within the boundaries of the District there are two primary aquifers, the Northern Trinity Aquifer, which is a major aquifer defined by the Texas Water Development Board (TWDB) and the Woodbine aquifer which is designated as a minor aquifer. The defining attribute of a major aquifer is that it provides significant quantities of groundwater over a large area, while a minor aquifer can deliver significant quantities of groundwater over a small area.

The geologic formations that make up the Northern Trinity Aquifer are Cretaceous-age sediments. The most abundant rock type in the Cretaceous-age strata in Texas is limestone, which covers the Edwards Plateau and much of central Texas. However, in the Northern Trinity Aquifer as one moves into north-central Texas, where the District is situated, the Cretaceous age sediments are sand-dominated formations with the exception of the Glen Rose Formation.

Geologic and stratigraphic studies of the units making up the Northern Trinity Aquifer started at the turn of the century between the 1800s and the 1900s with the studies of R.T. Hill which included counties within the District (Hill, 1891, 1894, 1901). Since that time, there have been several important studies of the stratigraphic units of the Northern Trinity Aquifer, including Hendricks (1957) and Fisher and Rodda (1966, 1967). In 2012, desiring to make improvements and updates to the 2004 Northern Trinity and Woodbine Aquifers GAM and to enhance understanding of the Northern Trinity and Woodbine aquifers, the Prairielands GCD and three other Groundwater Conservation Districts (North Texas GCD, the Northern Trinity GCD, and Upper Trinity GCD) in North Central Texas entered an inter-local agreement funding an updated GAM for the Northern Trinity and Woodbine aquifers.

Part of the model redevelopment included a comprehensive hydrogeologic framework of the entire Northern Trinity and Woodbine aquifers from the Colorado River to the south past the Red River in the north. The hydrogeologic framework was developed by Dr. Scott Hamlin of the Bureau of Economic Geology and provided update structural surfaces for the aquifers and the formations that comprise the aquifers and also mapped the dominant lithologies of the formations. The term lithology refers to the material that comprises a particular geologic unit. Common lithologic terms used to describe geology include gravel, sand, clay (shale), limestone and mixtures of the four lithologies. The lithologic character of a geologic unit is a product of the conditions it was deposited in with nearshore deposits generally more sand rich and off-shore depositional environments being dominated by shales or limestones. The study found that the Northern Trinity and Woodbine Aquifers of West Texas could be geographically subdivided into five regions by geologic and lithologic variability (Figure 2-1). The District lies mostly within region 4 and encompasses a small portion of region 2 in northwestern Johnson County and in northern Somervell County.

Figure 2-2 shows an interpreted geophysical log in Johnson County representative of region 4 hydrogeology. The log has been interpreted to define formation boundaries and dominant lithology within the formations. At this location the Woodbine is present at surface and is dominantly sandstone depicted as a yellow color on the log. The Washita/Fredericksburg Group is a regional confining unit that separates the Woodbine from the uppermost Trinity sand, the Paluxy Formation. The Glen Rose Formation separates the Paluxy from the sandstones, sands, and shales in the lower portion of the northern Trinity Group (collectively referred to as the Twin Mountains in region 2. In most of the District the formations that comprise the Twin Mountains, the Hensell Formation, the Pearsall Formation, and the Hosston Formation can be delineated. A detailed hydrogeologic framework for the aquifers can be found in Kelley and others 2014.

In this study, we evaluate the ASR suitability of the Woodbine, Paluxy, Hensell, Pearsall, and Hosston Formations which are dominated by sand lithology. Because AR occurs from the surface, we evaluated AR suitability for all aquifers outcropping within the District. The predominantly limestone formations (e.g., the Glen Rose and Fredericksburg/Washita Formations) were not evaluated for ASR suitability because the permeability and storativity of these limestone formations are considered to be too low for a successful ASR project. In the next two sections we discuss the fundamental hydrogeologic parameters, which form the basis for assessing the relative sustainability of ASR and AR techniques.

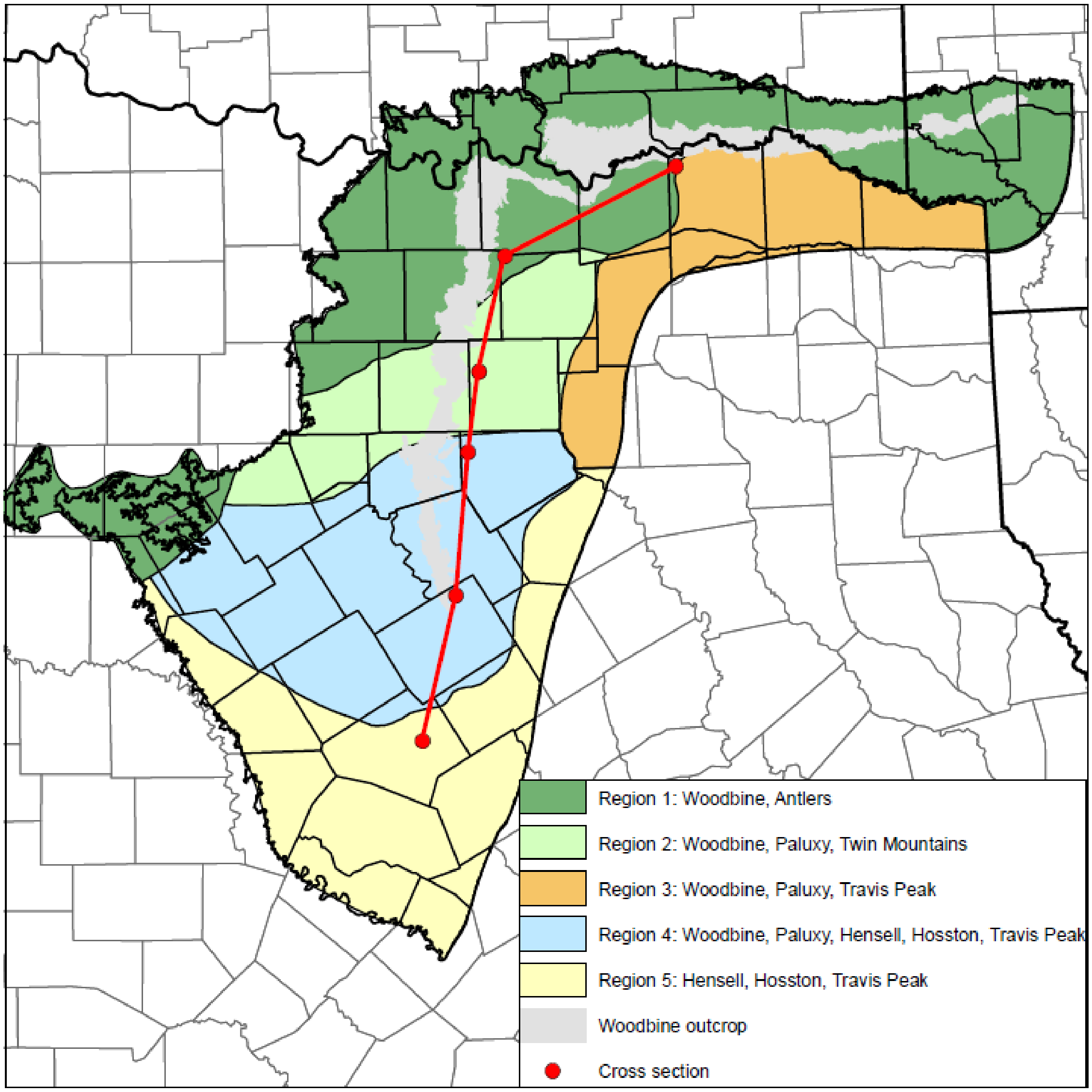

Figure 2-1 Northern Trinity GAM model extent and regions defined by stratigraphic and lithologic similarities (Kelley and others 2014).

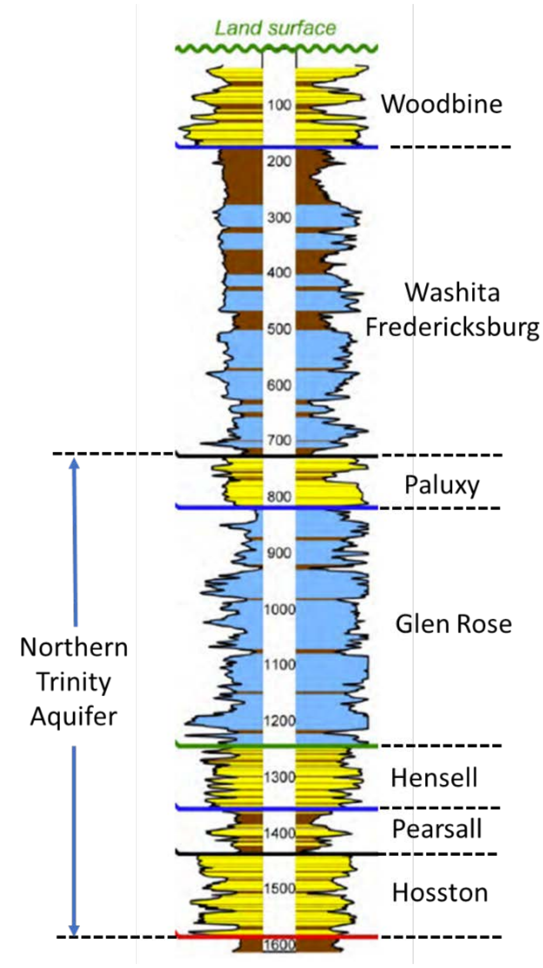

Figure 2-2 Geophysical Log in Johnson County showing Northern Trinity and Woodbine aquifer formations and dominant lithologies (after Kelley and others 2014).

3.0 SUITABILITY METRICS

To evaluate the suitability for ASR and AR across the District, several suitability metrics were defined which describe the suitability of a specific location for ASR or AR. These metrics may be descriptive of geology, hydrogeology and geography of a specific location. For both ASR and AR metrics have been categorized into three broad categories: hydraulic head metrics, aquifer metrics, and geographic metrics. Table 3-1 list the suitability metrics by category. Each will be discussed in the remainder of this section.

Table 3-1 Suitability Metrics by Category.

Metric Category	Aquifer Storage & Recovery	Aquifer Recharge
Hydralic Head	Available Drawdown	Depth to Water
	Availiable Drawup	
Aquifer	Effective Sand Hydraulic Conductivity	Horizontal Hydraulic Conductivity
	Net Sand Thickness	
	Aquifer Storativity	
	Storage Zone Depth	
	Aquifer Drift Velocity	
	Groundwater Quality	
Geography		Soils Vertical Hydraulic Conductivity
		Topographic Slope
		Land Use / Land Cover

3.1 Hydraulic Head Metrics

Summarizing hydraulic heads and regional groundwater flow is important to characterize the amount of water that can be recharged with ASR and AR and recovered with ASR. Hydraulic head is the elevation of the groundwater level in an aquifer and is typically measured in a well. Hydraulic head is a direct measure of the potential energy of groundwater. Therefore, groundwater flows from high hydraulic heads to low hydraulic heads. Hydraulic heads vary laterally and vertically in aquifers and, consequently, groundwater movement has a vertical as well as a horizontal component of flow. The head data used to evaluate suitability was derived from the 2010 calibrated NTGAM model heads. Model heads have the advantage of being regularly distributed across each aquifer within the District and are constrained to the field observations. Hydraulic heads are important because they define three key suitability metrics; depth to water, available drawdown and available drawup.

3.1.1 Depth to Water and Available Drawdown

The depth to water is the vertical distance between the land surface elevation and the hydraulic head within the aquifer and is an important variable in both ASR and AR. For AR, the depth to water from ground surface defines the thickness of the vadose (partially unsaturated) zone. The thickness of the vadose zone is equal to the elevation of land surface minus the depth to the water table. Vadose zone thickness impacts the suitability of AR both in terms of the available storage potential and the ability for the recharged water to maintain high saturation and therefore high infiltration rates. When the vadose zone is thin (i.e., < 30 ft) it is easy to maintain high saturation and high infiltrations rates, but storage potential is minimal. At greater depths (> 300 ft) storage potential is immense, but the time and volume of water required to reach the target aquifer increases significantly. The optimum depth to water for AR is likely somewhere between 30-300 feet (Shaw and Others, 2020).

The available drawdown is the vertical distance the aquifer hydraulic head can be decreased during an ASR recovery cycle. As for normal groundwater production, increases in available drawdown generally relate to increases in production at a given well. Available drawdown in this study is calculated as the difference between the NTGAM head simulated in 2010 and the bottom of each aquifer of interest. In reality there are practical limits to available drawdown generally caused by pump elevation and a desire to keep the aquifer head above the top of a confined aquifer. Because this study normalizes each metric, defining available drawdown from the base of each aquifer is representative. There is no explicit intent to recover recharged water in AR, for this reason, available drawdown is not considered an important hydrogeologic parameter for AR. Figure 3-1 shows a schematic of available drawdown as defined in this study.

3.1.2 Drawup (Available Injection Head)

Drawup, or the available injection head, in combination with the aquifer transmissivity defines the rate at which an ASR system can be recharged. For purposes of this study we have defined available drawup as the absolute value of the difference between the NTGAM simulated 2010 hydraulic and ground surface elevation. In most confined areas in the Northern Trinity Aquifer, heads are below ground surface. From an operational perspective, the ASR operator can apply positive pressure (generally less than 60 psi) at ground surface to increase injection pressures and rates. Figure 3-1 shows this. We did not consider an applied surface pressure in our calculation of available drawup because it would be a constant and would factor out of the normalized metric value.

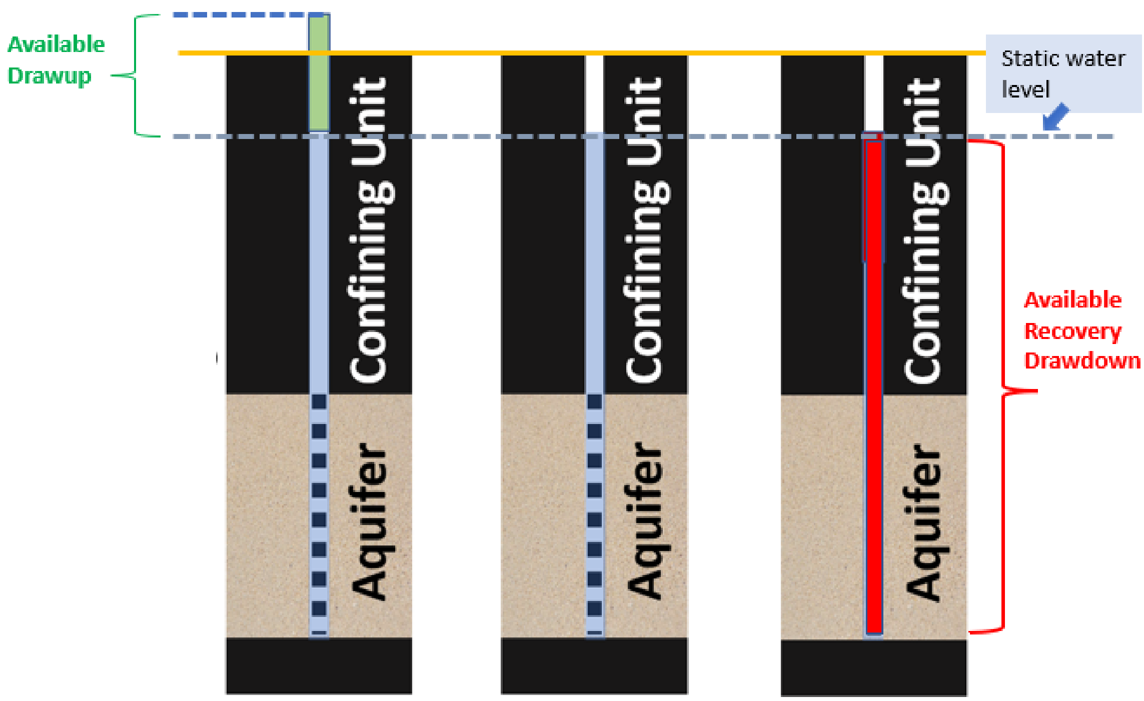

Figure 3-1 Schematic of the available drawdown and available drawup metrics used to characterize ASR suitability.

3.2 Aquifer Based Metrics

3.2.1 Hydraulic Conductivity Based Metrics

Hydraulic conductivity, represented as "K", is a property of an aquifer that describes the ease with which a fluid (usually water) can move through pore spaces or fractures. It depends on the pore structure of the aquifer deposits and on the degree of saturation, and on the density and viscosity of the fluid. Hydraulic conductivity has dimensions of length per time (i.e., feet per day (ft/day))).

The horizontal hydraulic conductivity is an important variable in predicting well field recharge and recovery rates in ASR. Generally, the hydraulic conductivity of sandy aquifer units are orders of magnitude greater than the hydraulic conductivity of shale and clay units. For this reason, the study estimates an effective sand horizontal hydraulic conductivity for the sand dominant aquifers: the Woodbine, Paluxy, Hensell, Pearsall, and Hosston formations. The effective horizontal hydraulic conductivity (K_{eff}) was calculated for each formation by:

$$K_{eff} = \frac{(K_h b_{sand})}{b_{layer}}$$

where K_h is the horizontal hydraulic estimated in the NTGAM, b_{sand} is the thickness of the sand interbeds present in each formation, and b_{layer} is the total thickness of the formation. Net sand thickness and aquifer layer thickness are derived from the NTGAM.

For the suitability of AR we used two hydraulic conductivity metrics. One captures the ease that recharge water can infiltrate into the aquifer from land surface (soil vertical hydraulic conductivity) and the other is a bulk estimate of the aquifers ability to receive the recharge in the saturated zone (horizontal hydraulic conductivity).

For the AR analysis, the vertical hydraulic conductivity of the soil and top-most aquifer control the flow rate of recharged water. Soil vertical hydraulic conductivities were approximated using soils data from the USDA (SSURGO). There are 403 unique soil units identified within the District. Each soil unit is vertically divided into soil horizons and for each soil horizon the saturated vertical hydraulic conductivity has been measured. For soil units with more than one soil horizons the saturated hydraulic conductivity was estimated by calculating the harmonic mean. The horizontal aquifer hydraulic conductivity was taken directly from the NTGAM. Because recharge is from above in AR, we used a bulk horizontal hydraulic conductivity rather than effective sand hydraulic conductivity.

3.2.2 Aquifer Storativity

The terms storativity, specific storage, and specific yield are terms used to define the amount of water that can physically be removed from, or added to, an aquifer when the water level in the aquifer changes. High aquifer storativity is desirable because a higher storativity enables more water to be recharged for a given increase in head. In general terms, when water is removed from an aquifer by pumping or is added to an aquifer by recharge, the amount of water stored in the aquifer changes.

Storativity is defined as the volume of water that an aquifer releases from storage under a unit decline in hydraulic head (Freeze and Cherry, 1979). Because of physical differences between unconfined and confined aquifers, storativity is defined differently for the two aquifer conditions. An unconfined aquifer is one in which the water levels in wells are below the top of the aquifer and the top of the aquifer is at atmospheric pressure. For an unconfined aquifer, the storativity equals the specific yield. Specific yield values account for the amount of water that drains from the aquifer pores following a drop in the water level. For most unconsolidated aquifers, reported values for specific yield for calibrated regional models fall within a relatively narrow range, between 0.1 and 0.3. Because specific yield dictates storage potential in an unconfined aquifer it is an important factor to consider in AR. There few field measurements to characterize the spatial variability of specific yield throughout the District. For this reason, it was not incorporated as a hydrogeologic parameter evaluated in this study.

A confined aquifer is one in which the water levels in the wells rise above the top of the aquifer. For a confined aquifer, storativity equals the aquifer thickness multiplied by the aquifer specific storage. Unlike specific yield, specific storage values typically have a range of several orders of magnitude. Factors that affect the specific storage values are lithology and depth of burial. Lithology is a factor because clay materials are more compressible than sand and, therefore, are more susceptible to changes in porosity with changes in pressure. Depth of burial is a factor because the compressibility of unconsolidated deposits is a nonlinear function of pressure. Values for specific storage in sand and clay aquifers typically range between 0.001 and 0.000001 1/feet (ft^{-1}) (Young and Kelley, 2006; Young et al., 2009).

As part of the Northern Trinity and Woodbine aquifer GAM redevelopment, aquifer storage values for the Northern Trinity and Woodbine aquifers were reviewed. Based upon conceptual considerations that control specific storage, Shestakov (2002) developed a semi-empirical relationship to estimate specific storage. In the NTGAM study, the relationship by Shestakov (2002) was modified to account for a heterogeneous medium with various percentages of shale, limestone, and sand as observed in the northern Trinity Aquifer and constrained to fit to literature values for specific storage in the northern Trinity Aquifer.

3.2.3 Aquifer Depth

An important consideration when developing an ASR project is the depth to the aquifer to be used for storage. This depth impacts several factors including cost of the well, energy costs associated with excessive lift depths, groundwater temperature and the potential for air entrainment during recharge. Aquifer depth was derived from the NTGAM and used as an ASR suitability metric.

3.2.4 Aquifer Drift

Aquifer drift is important to the recoverability of the water that is stored in an ASR project. The recovery efficiency of an ASR project is defined as the volume of water recharged divided by the volume of water recovered expressed as a percent. Because of mixing of the recharge water with the aquifer groundwater and because the groundwater is moving at some velocity (drift) in the subsurface, recovery efficiency is generally less than 100%. We handle aquifer water quality as a suitability metric.

To estimate aquifer drift, we use groundwater Darcy velocity calculated by the NTGAM and divide by an effective porosity of the aquifer to get an ambient groundwater velocity within an aquifer. Porosity of an aquifer is defined by the volume of the voids divided by the total volume. In this study we assumed a constant porosity of 0.2 in all aquifers with unconsolidated sands and sandstones.

3.2.5 Water Quality Considerations for ASR

ASR involves injecting treated water via wells into aquifers and storing the water for future recovery. Injected water is treated because TCEQ requires that water injected into ASR wells be treated to standards set forth in the federal Safe Drinking Water Act before issuing a permit under §331.186(a). During storage in an aquifer, changes in the chemical characteristics of the injected water can result from physical, chemical, and biological reactions. Physical reactions include stratification of waters due to differences in density. Chemical reactions may cause precipitation of solids due to: (1) reactions between the injected water and the native water in the storage zone of the aquifer, and (2) reactions between the injected water and the rock matrix that compose the aquifer. Biological reactions may include bacterial growth that creates clogging around well screens and impacts well efficiency. Biological reactions may also mobilize metals such as arsenic in the groundwater. Because physical, chemical, and biological reactions can affect the recharge and recovery efficiency, water quality is a key consideration for design and implementation of an ASR system.

The TWDB groundwater database (http://www.twdb.texas.gov/groundwater/faq/faqgwdb.asp) is the most comprehensive water quality data source and contains data for over 140,000 groundwater wells in Texas. Ideally, the available data would contain sufficient information to characterize the geochemistry of the groundwater and the vertical differences between aquifers at a proposed ASR location. Knowledge of the vertical differences in water quality among the aquifers of interest is one of many factors that influence which aquifers, and which zones within each aquifer, would be best suited for target recharge zones. This level of investigation is not practical at the District scale.

Total Dissolved Solids (TDS), the sum of all cations and anions in solution, is often used as a general indicator of water quality and is one of the most commonly measured water quality parameters. The TDS standard for drinking water is regulated as a secondary standard relating to aesthetics rather than health hazards. The EPA has set a limit of 500 milligrams per liter (mg/L), while TCEQ has a set a limit of 1,000 mg/L for TDS, the upper limit of fresh water as defined by the TWDB. In general, TDS is expected to increase with depth below land surface as the groundwater acquires the chemical imprint of the minerals encountered along its flow path.

TDS concentrations in 606 wells were evaluated within the District. The average TDS concentration was 776 mg/L, 90% of the TDS measurements were less than 1,400 mg/L, and 99% of TDS measurements were under 2,000 mg/L. TDS concentrations were greatest in the downdip portions of each aquifer, as expected. From an operational viewpoint of an ASR facility, TDS concentration values in the range of 1,000 mg/L to 2,000 mg/L are equally acceptable. Given that 99% of TDS fell within this range, TDS distributions (i.e., more generally water quality) may not have a significant influence on the success of an ASR site within the District. It is likely that site specific trace metals would be important to the recoverability efficiency and success of ASR.

3.3 Geographic Based Metrics

AR strategies, except for LID strategies, generally have a large surface footprint. For this reason, topography and land use are important metrics that need to be considered.

AR strategies that utilize infiltration basins or spreading areas need to be situated in flat areas. If there is a considerable slope across a spreading area, infiltration potential would be reduced because water will run off the surface rather than infiltrate. Runoff also has the potential to mobilize fine-grained sediments. These fine-grained sediments would accumulate in low lying areas of an infiltration basin or spreading area and reduce the infiltration capacities in these areas. Land surface slope was calculated using a Digital Elevation Model (DEM) with a 10-foot by 10-foot resolution (USGS, 2020).

Land use was not incorporated into the TWDB's statewide AR suitability study because it was not relevant at the large spatial resolution of the study. INTERA integrated land use data in this AR suitability metrics because of the practical constraints land use can have on an AR project within the District. Land use data, available at a 30-meter by 30-meter spatial resolution, was acquired from NOAA (2016). The NOAA data set has 15 different land use types. INTERA considered the practicality and costs associated with an AR project situated in each land use type.

4.0 Methods

The method used to evaluate the relative suitability of ASR and AR within the District used in this study largely followed the methods used in the statewide ASR and AR study (Shaw and Others, 2020), but was modified to use the higher resolution data available at the District scale. All suitability metrics were evaluated on the NTGAM grid, which consists of quarter-mile by quarter-mile grid cells. Because the slope data and land use data were available at a higher spatial resolutions then the NTGAM grid, the two data sets were scaled to match the resolution of the NTGAM. For each NTGAM cell, the average of all slope cells within the NTGAM cell was assigned, for land use the most dominant land use type in each NTGAM cell was assigned.

The statewide study used a scoring methodology based on multi-attribute utility theory (MAUT), which forms a structure for making decisions when many different variables exist. In the MAUT approach, each suitability parameter (i.e., the parameters discussed in Section 2) is mapped onto a utility curve where the most suitable parameter score is set to one and the least suitable parameter score is set to zero. Each suitability parameter discussed in Section 3 was mapped onto a utility curve and the values are listed in Table 4-1 and Table 4-2. Appendices A-E show the spatial distribution of each mapped suitability parameter reviewed in the ASR analysis for the Woodbine, Paluxy, Hensell, Pearsall, and Hosston formations. Appendix F shows the spatial distribution of the suitability parameters reviewed in the AR analysis. The mapped parameters are then multiplied by the associated weight list in Table 4-3 and Table 4-4. The weighted suitability parameter scores are then summed for ASR and for AR giving the total suitability score.

To simplify for display and discussion purposes the total suitability scores were normalized again onto a zero to one scale. A value of zero corresponds to the minimum possible suitability score on

Table 4-1 and Table 4-2 (e.g., 0.6 in ASR and 0.29 in AR), while a value of one corresponds to the maximum possible suitability score (e.g., 4.5 in ASR and 3.25 in AR). The final normalized suitability scores for were categorized as low (< 0.3), medium (0.3-0.7), and high (> 0.7). The thresholds values applied in ASR and AR were based on inspection of the final scoring distributions.

Table 4-1 Proposed hydrogeological parameters and associated scoring for ASR.

Hydrogeological Parameter Scoring for ASR							Data Source(s)
Storage zone depth	Depth (ft bgs)	< 200	200-1000	1000-2000	> 2000		NTGAM
	Score	0.1	1	0.75	0.5		
Sand horizontal hydraulic conductivity	K_{sand} (ft/day)	< 1	1 to 3	3 to 10	10 to 30	> 30	NTGAM
	Score	0.2	0.3	0.5	0.8	1	
Drawup Available	Drawup (ft)	< 50	50-100	100-400	> 400		NTGAM
	Score	0.1	0.2	0.2-0.9	1		
Drawdown available	Drawdown (ft)	< 50	50-100	100-400	> 400		NTGAM
	Score	0.1	0.2	0.2-0.9	1		
Sand Thickness	Thickness (ft)	< 50	50-250	> 250			NTGAM
	Score	0.1	0.5-1	1			
Aquifer storativity	S (-)	< $1e^{-5}$	$1e^{-5}$ to $1e^{-4}$	$1e^{-4}$ to $1e^{-3}$	$1e^{-3}$ to $1e^{-2}$	> $1e^{-2}$	NTGAM
	Score	0.2	0.4	0.6	0.8	1	
Drift velocity	Drift velocity (ft/y)	< 20	20-100	100-1000	> 1000		NTGAM, Aquifers of Texas (2011)
	Score	1	0.75	0.5	0.1		
Groundwater quality	TDS (mg/L)	< 300	300 - 100	1000-1500	1500-3000	> 3000	NTGAM, GWDB
	Score	1	0.9	0.8	0.6	0.5	

Table 4-2 Proposed hydrogeological parameters and associated scoring for AR.

Hydrogeological Parameter Scoring for Aquifer Recharge							Data Source(s)
Vertical hydraulic conductivity of soils	**K_{soils} (ft/day)**	< 5	5 to 20	> 20			SSURGO
	Score	*0.1*	*0.5*	*1*			
Horizontal hydraulic conductivity	**K_{aq} (ft/day)**	< 1	1 to 3	3 to 10	10 to 30	> 30	NTGAM
	Score	*0.2*	*0.3*	*0.5*	*0.8*	*1*	
Topographic slope	**K_{sand} (degrees)**	< 2	2 to 5	> 5			DEM
	Score	*1*	*0.5*	*0.01*			
Depth to water table	**Depth (ft bgs)**	0	1 to 10	10 to 30	30 to 300	> 300	NTGAM
	Score	0.01	0.2	0.5	1	0.5	
Land use	**Use type**	Developed, open space, low, medium, high intensity)	Barren Land	Deciduous, Evergreen, and Mixed Forest	Shrub/ Scrub	Pasture/ Hay	National Land Cover Database (NLCD)
	Score	*0.6, 0.3, 0.2, 0.1*	*1*	*0.5, 0.5, 0.5*	*1*	*1*	
	Use type	Cultivated Crops	Woody Wetlands	Emergent Herbaceous Wetlands			
	Score	*1*	*0.2*	*0.2*			

Table 4-3 Parameter weights associated with ASR scores.

Weighting Scheme for ASR Suitability		
Parameter name	**Weight**	**Notes**
Storage zone depth	0.25	Lower weight because depth generally drives challenges that can be overcome with careful design.
Sand horizontal hydraulic conductivity	1	Key parameter for overall well recharge/production rates.
Drawup Available	0.5	Can limit recharge rate, but wellheads can be designed to withstand ~70 psi pressure above ground surface, so weighted medium.
Drawdown available	0.5	Very site specific, so weighted medium. Can be overcome by increasing local heads through recharge, but this strategy is not possible at all sites.
Sand Thickness	1	Key parameter separating more suitable from less suitable aquifers, so weighted high.
Aquifer storativity	0.5	Drives shorter term hydraulic response, but does not typically affect longer term performance, so weighted medium.
Drift Velocity	0.75	Can be a critical factor for recoverability, but can overcome by large buffer zones or with additional pumping wells.
Groundwater quality	NA	Can be a critical factor for recoverability, but can also be overcome with treatment and injection strategies. Influence of groundwater quality can be better assessed at site-specific scale.

Table 4-4 Parameter weights associated with AR scores.

Weighting Scheme for AR Suitability		
Parameter name	**Weight**	**Notes**
Vertical hydraulic conductivity of soils	0.25	While vertical hydraulic conductivity is very important for AR infiltration rates, estimates were limited by very shallow SSURGO dataset. Because overcoming limited conductivity using excavation or vadose zone wells is very site-specific this factor was weighted low to offset overall uncertainty.
Horizontal hydraulic conductivity	1	Key parameter for moving infiltrating water into deeper aquifer system.
Topographic slope	0.5	Can often be overcome through engineering, so weighted medium.
Depth to water table	1	Critical for viability of AR and fairly well-known, so weighted high.
Land use	0.5	Broad factor separating more suitable from less suitable areas, but some land use limitations can be overcome through engineering, so weighted medium.

5.0 Results/Discussion

5.1 Suitability for ASR

The final ASR suitability scores indicate that of the five aquifer units studied the Paluxy, Hensell, and Pearsall fell completely within the medium suitability category (Figure 5-2,Figure 5-3,Figure 5-4). The Woodbine and Hosston also fall mostly within the medium suitability category, but there are large portions within Ellis County, which are considered highly suited for ASR (Figure 5-1 and Figure 5-5). These highly suited regions coincide with the areas where sand thickness is greatest in the Woodbine and Hosston (Appendix A and Appendix E). There are no areas within the District that are considered to be of low suitability for ASR.

All aquifers, except for the Pearsall, have large areas that fell just below highly suitable (i.e., within 0.6-0.7). The Pearsall aquifer generally has the lowest relative ASR suitability, which is expected given the hydrogeologic characteristics of the unit described in Section 2. While this study focused on evaluating ASR suitability individually for each aquifer, in practice one could install an ASR well that that targets multiple aquifers. For example, if a stakeholder wanted to site an ASR well in the Lower Trinity aquifer system, the ASR suitability maps for the Hensell, Pearsall, and Hosston could be summed (Figure 5-3 - Figure 5-5). The areas with the highest sum would have the greatest potential for a successful ASR operation.

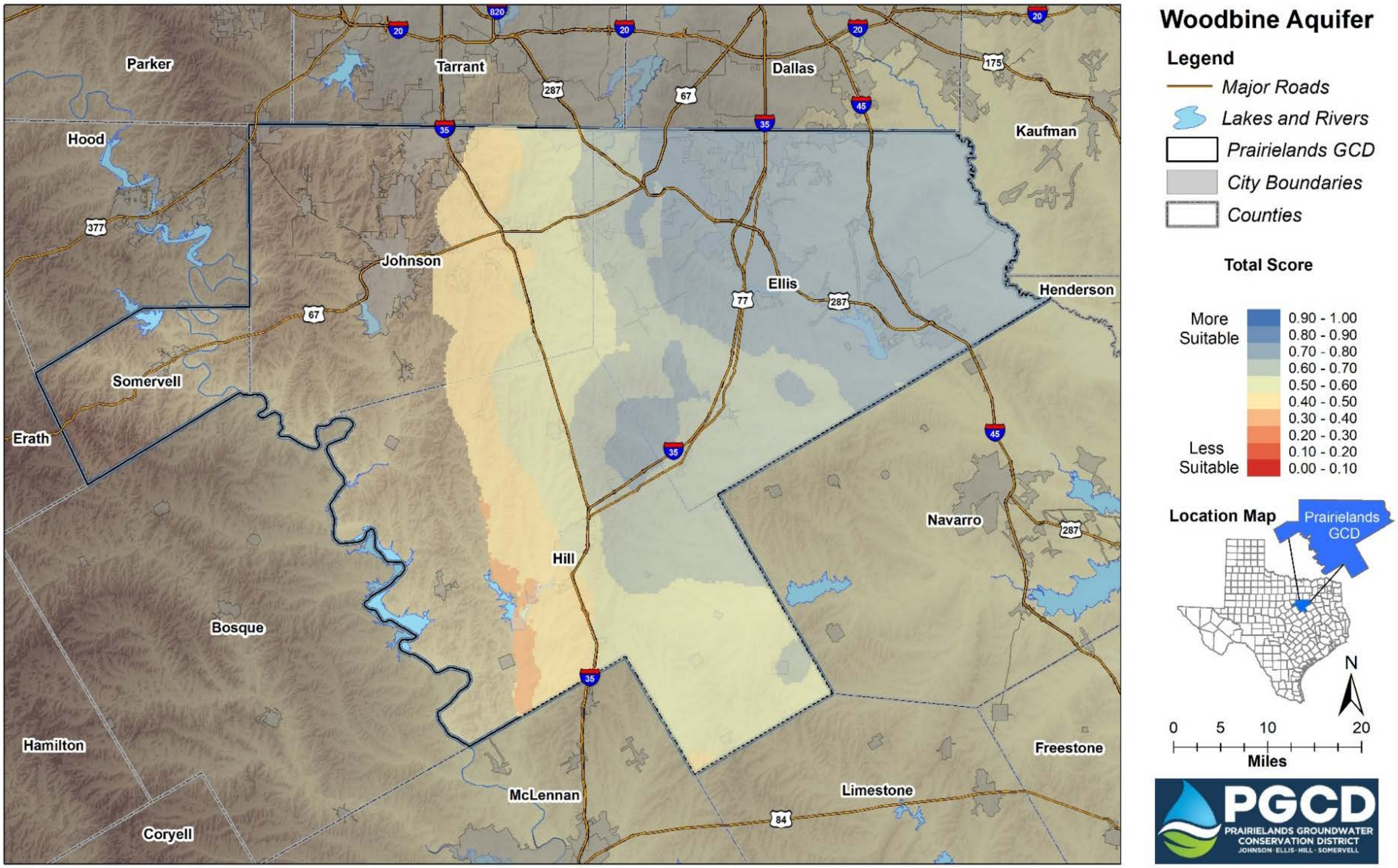

Figure 5-1 ASR suitability score for the Woodbine aquifer.

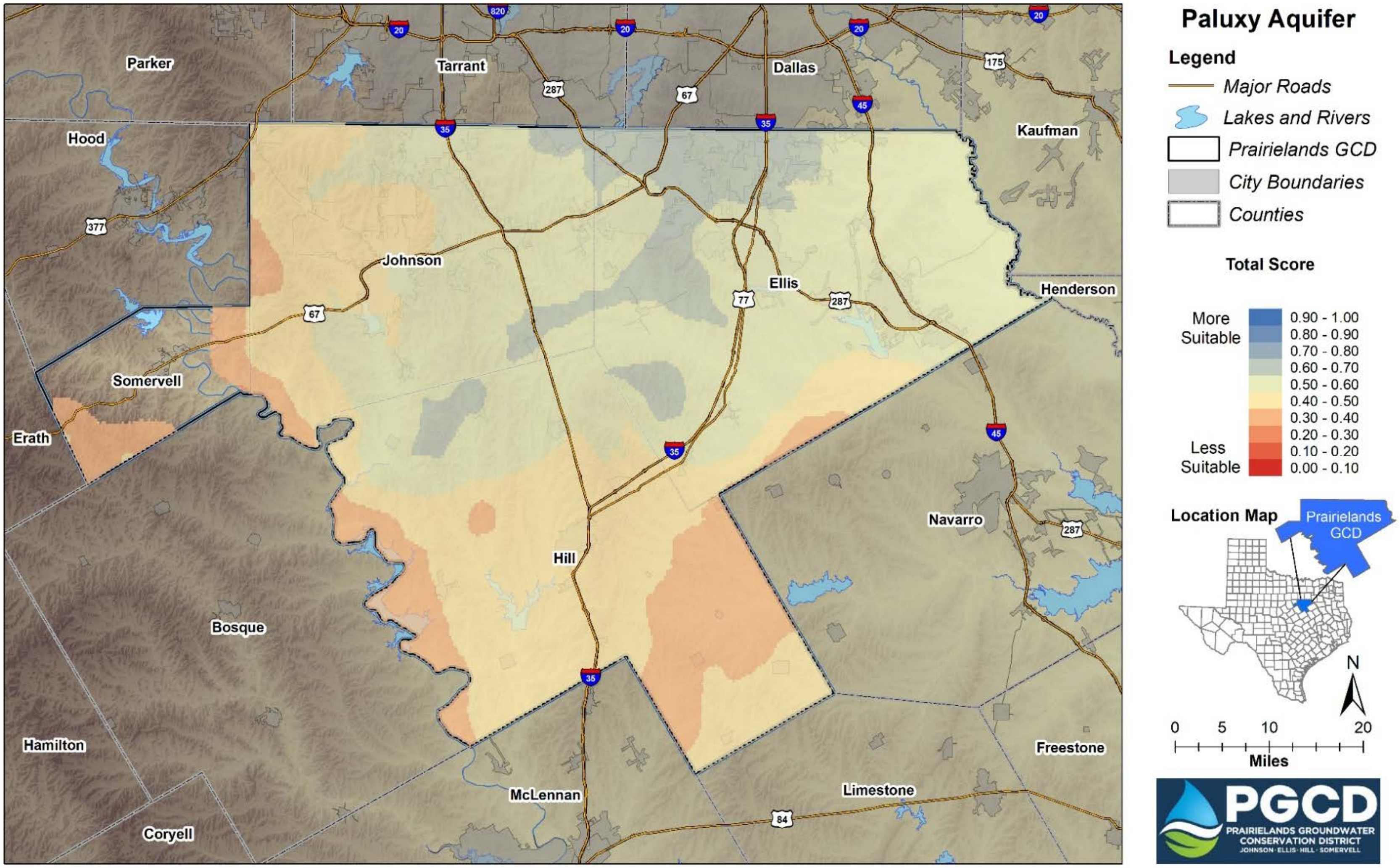

Figure 5-2 ASR suitability score for the Paluxy aquifer.

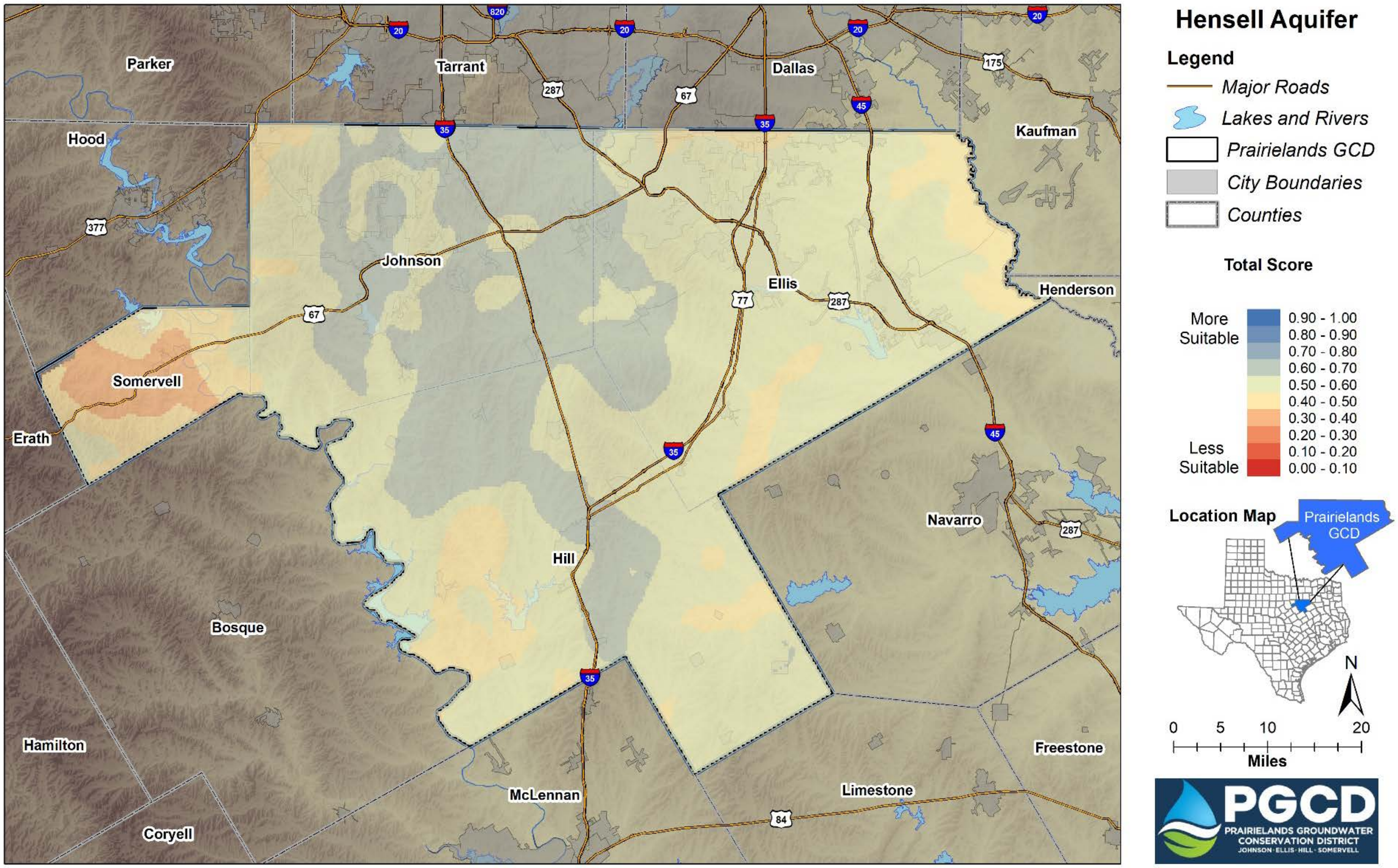

Figure 5-3 ASR suitability score for the Hensell aquifer.

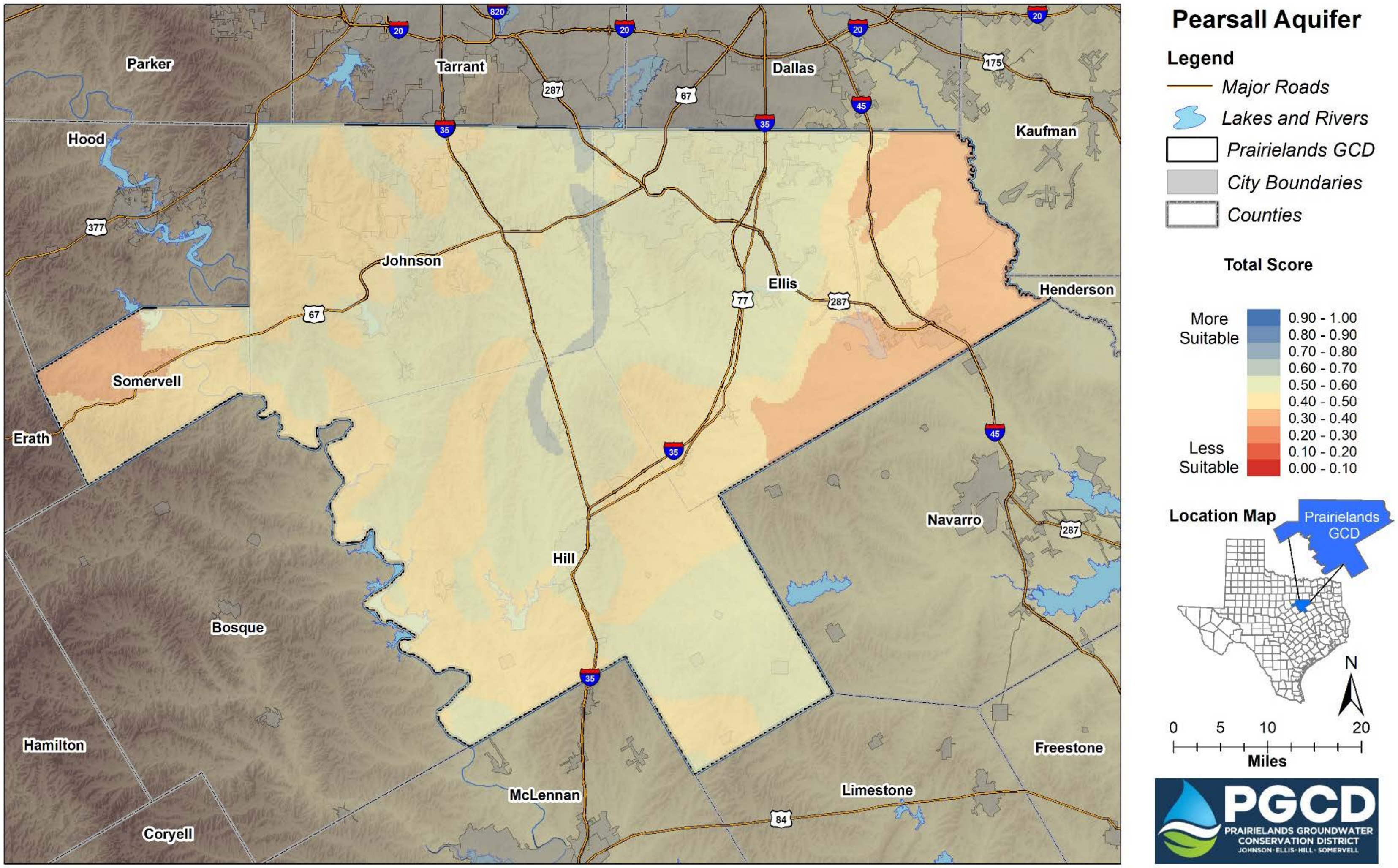

Figure 5-4 ASR suitability score for the Pearsall aquifer.

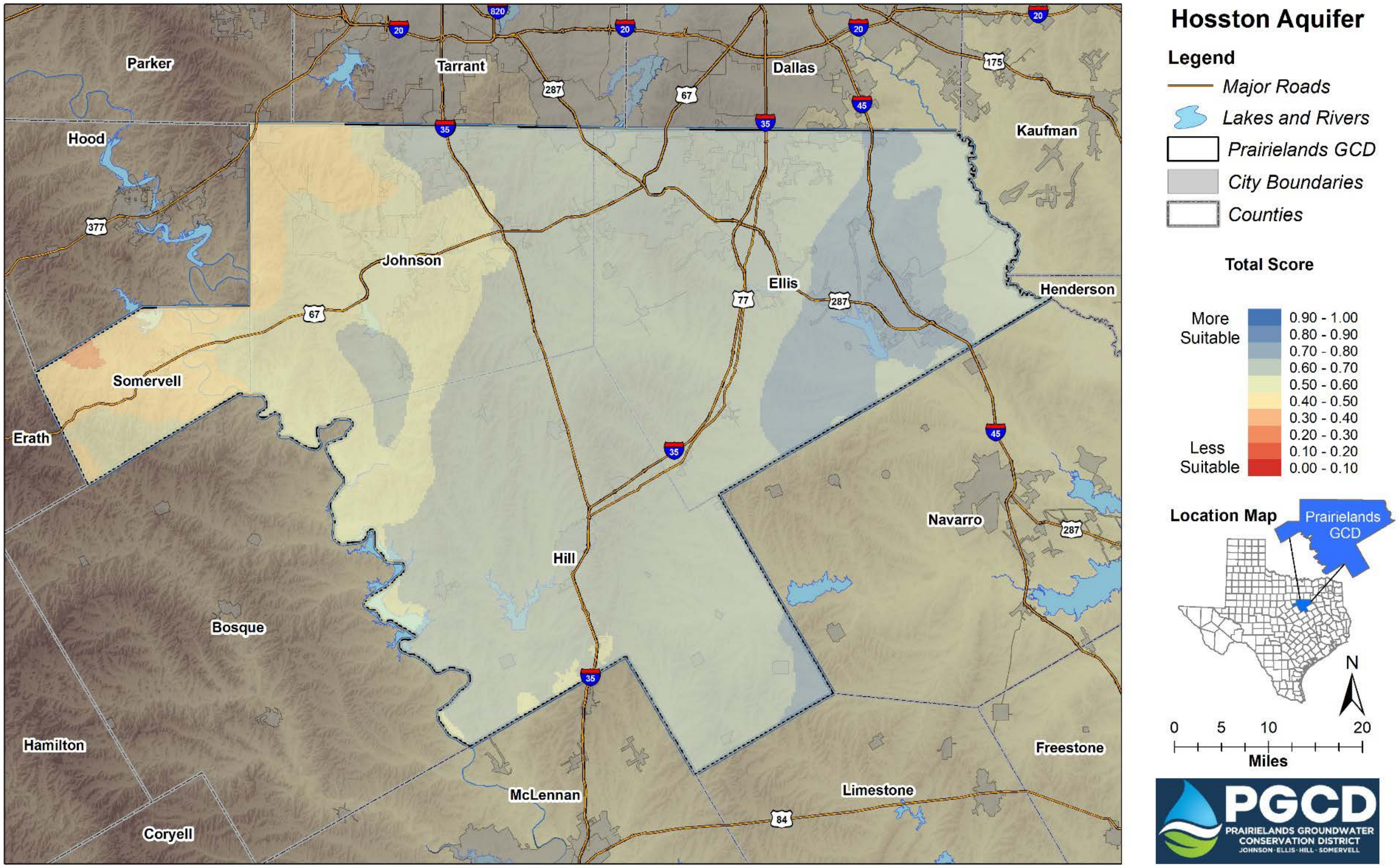

Figure 5-5 ASR suitability score for the Hosston aquifer.

5.2 Suitability for AR

The final AR suitability scores are shown in Figure 5-6. The shaded vs. unshaded areas in Figure 5-6 distinguish areas where the primary aquifer units are in subcrop from areas where they are in outcrop. The Woodbine and Paluxy are the only two aquifers that outcrop within the District. If the primary goal of an AR project is to offset groundwater pumping by increasing recharge to an aquifer, then it is important that these projects be located in areas where the aquifer units outcrop. Areas where the primary aquifers are in subcrop can still benefit from an AR project, but the recharge potential will depend on the hydraulic connectivity between the shallow subsurface and the underlying aquifer units. In areas where the shallow subsurface is comprised of homogeneous, uncompacted coarse-grained sediments, which tend to have the greatest vertical hydraulic conductivity, the recharge potential would be greater than areas with dense fine-grained units or intact limestone (i.e., units with much lower vertical hydraulic conductivity values). The site-specific hydrogeology of the area between the top of the shallowest aquifer and ground surface is key to applicability of AR projects.

The two hydrogeologic parameters that have the greatest influence on the distribution of AR suitability scores are the hydraulic conductivity of the topmost aquifer and water table depth. The spatial distribution of these two parameters are shown in Appendix F. Comparing the map of AR suitability results (i.e., Figure 5-6) to the map of water table depths in Appendix F, it is clear that less suitable areas for AR are in locations where the water table is shallow. The hydraulic conductivity of the topmost aquifer map in Appendix F indicates that the hydraulic conductivity of the topmost aquifer is less than 1 foot/day throughout the District, with the expectation of areas where the Paluxy outcrops. This results in limited variability in the hydraulic conductivity metric which makes the suitability score insensitive to this metric. It is highly unlikely that this nearly homogenous vertical hydraulic conductivity field represents reality. Because of the limited hydrogeologic data available in the shallow subsurface throughout the District, all hydrogeological parameter estimates made in the shallow portions of the NTGAM are uncertain. The uncertainty associated with the hydrogeological parameters estimated in the NTGAM generally decreases with depth because more information is available at the depths where the majority of groundwater pumping occurs within the District. In this study, the hydraulic conductivity of the topmost aquifer, which should be one of the key drivers of AR suitability, has minimal influence on the spatial distribution of AR.

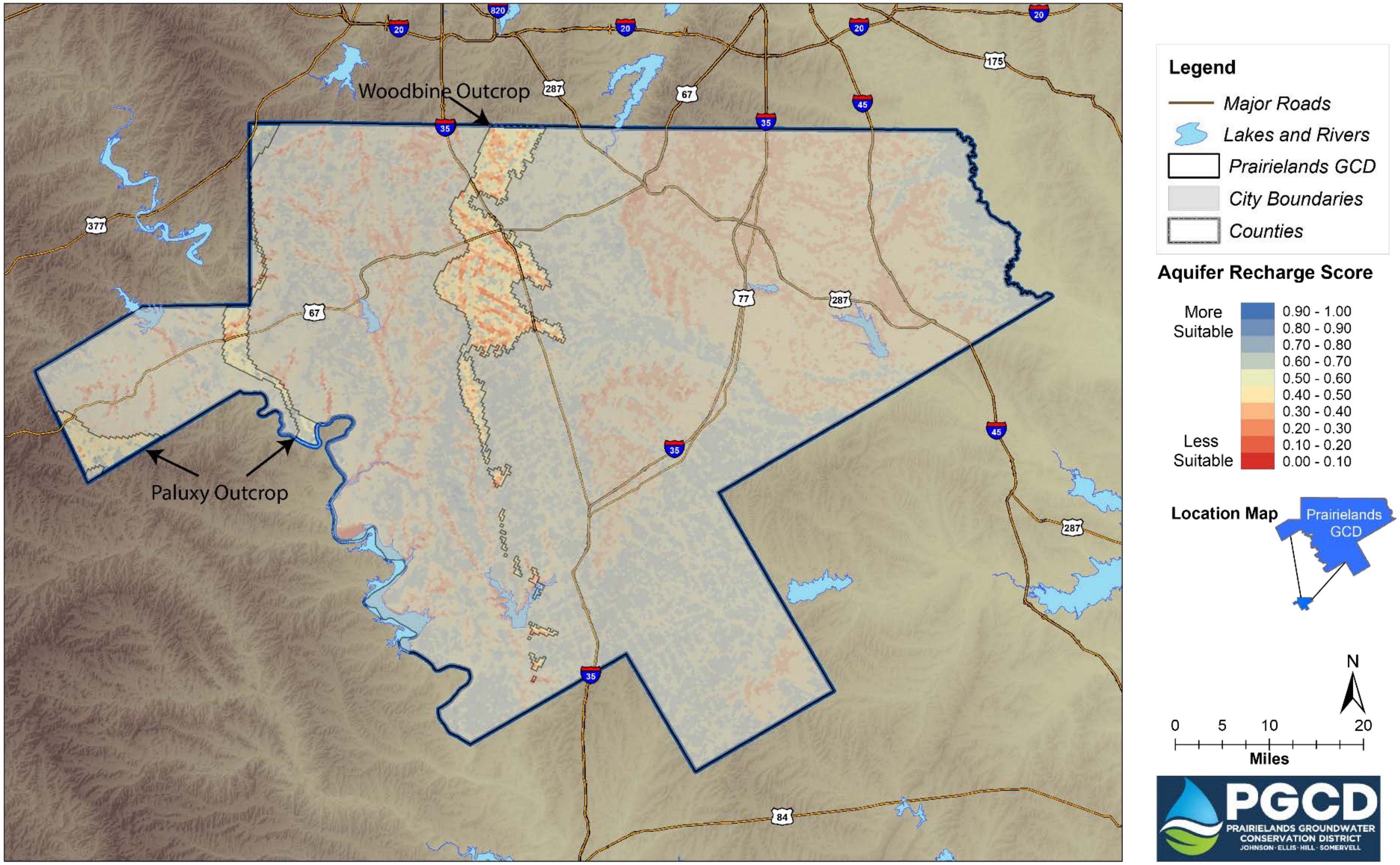

Figure 5-6 AR suitability score.

6.0 Conclusion

This project has resulted in creation of datasets that will help guide siting of ASR and AR projects which have the potential to improve groundwater supplies and quality within the District. All GIS datasets generated as part of this project will be made available to the District. The ASR and AR suitability maps illustrate which parts of the landscape and which aquifers may be most amenable to development of new ASR and AR projects. The ASR suitability map shows that the primary aquifers in the District are generally well suited for ASR projects. AR suitability is highly variable throughout the District because it depends on the nature of soil and rock conditions above the shallowest aquifer, land use and vegetation, and the depth to underlying water table. Because of the general lack of hydrogeologic data between the top of the shallowest aquifer and ground surface the AR suitability map is uncertain.

Results from this project can be used for preliminary screening of potential ASR and AR sites, but should be considered in a relative context. The siting and design of MAR projects is very site-specific and considers many factors in addition to the factors considered in this study (geology, hydrogeology and geography). Other factors that may need to be taken into account when considering development of new ASR and AR projects, including: source water, access to land, interest of landowners and tenants, possible ancillary benefits (e.g., improvements to streamflow or wetland conditions), and engineering and operations costs. However, this study provides a framework to identify portions of the District where the aquifers and topography are relatively more suitable for MAR. This study is a precursor to the typical phased MAR design and implementation process which is adaptive in nature and is driven by collection of site-specific data and information.

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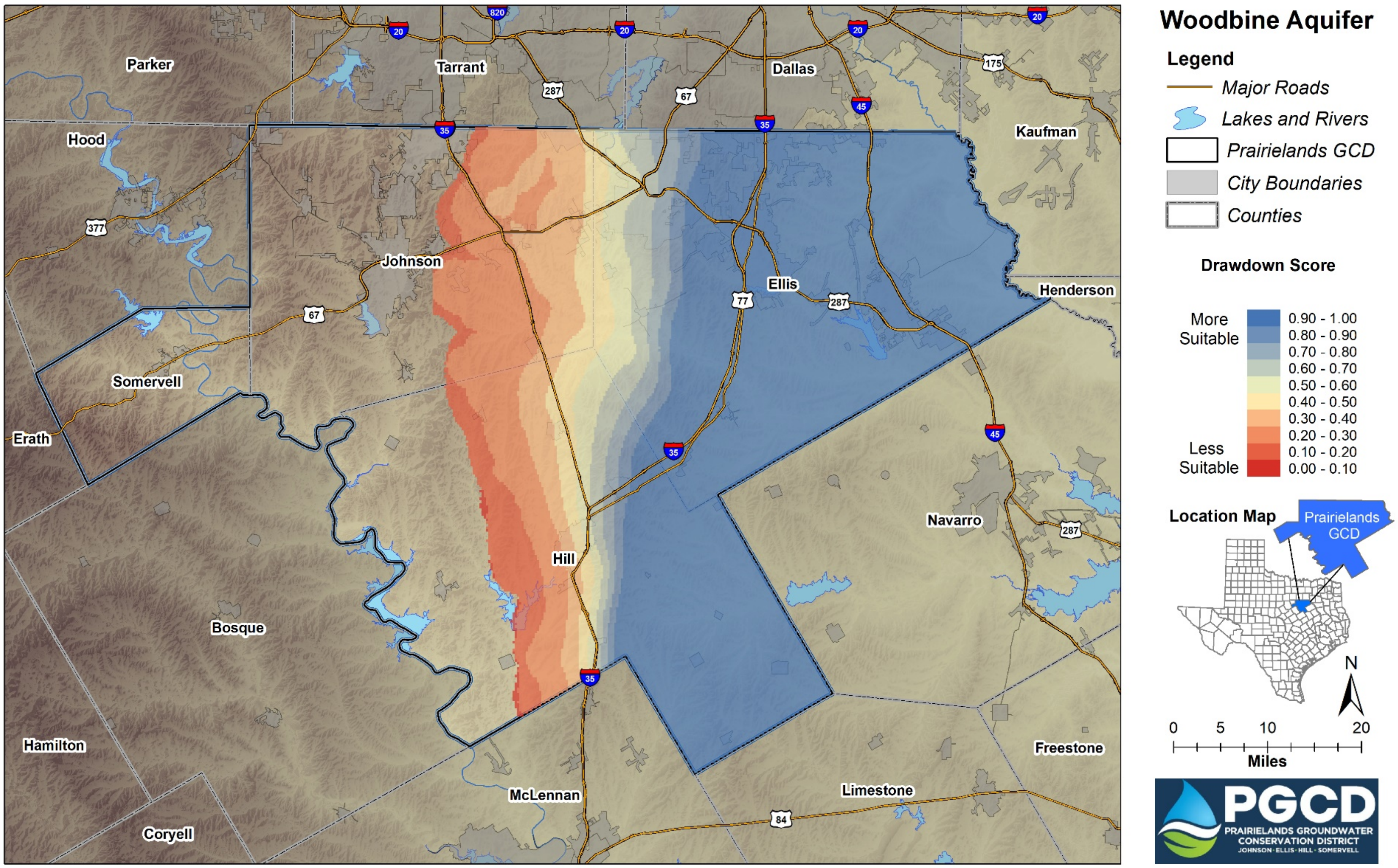
APPENDIX A:
WOODBINE ASR - HYDROGEOLOGIC PARAMETER SCORES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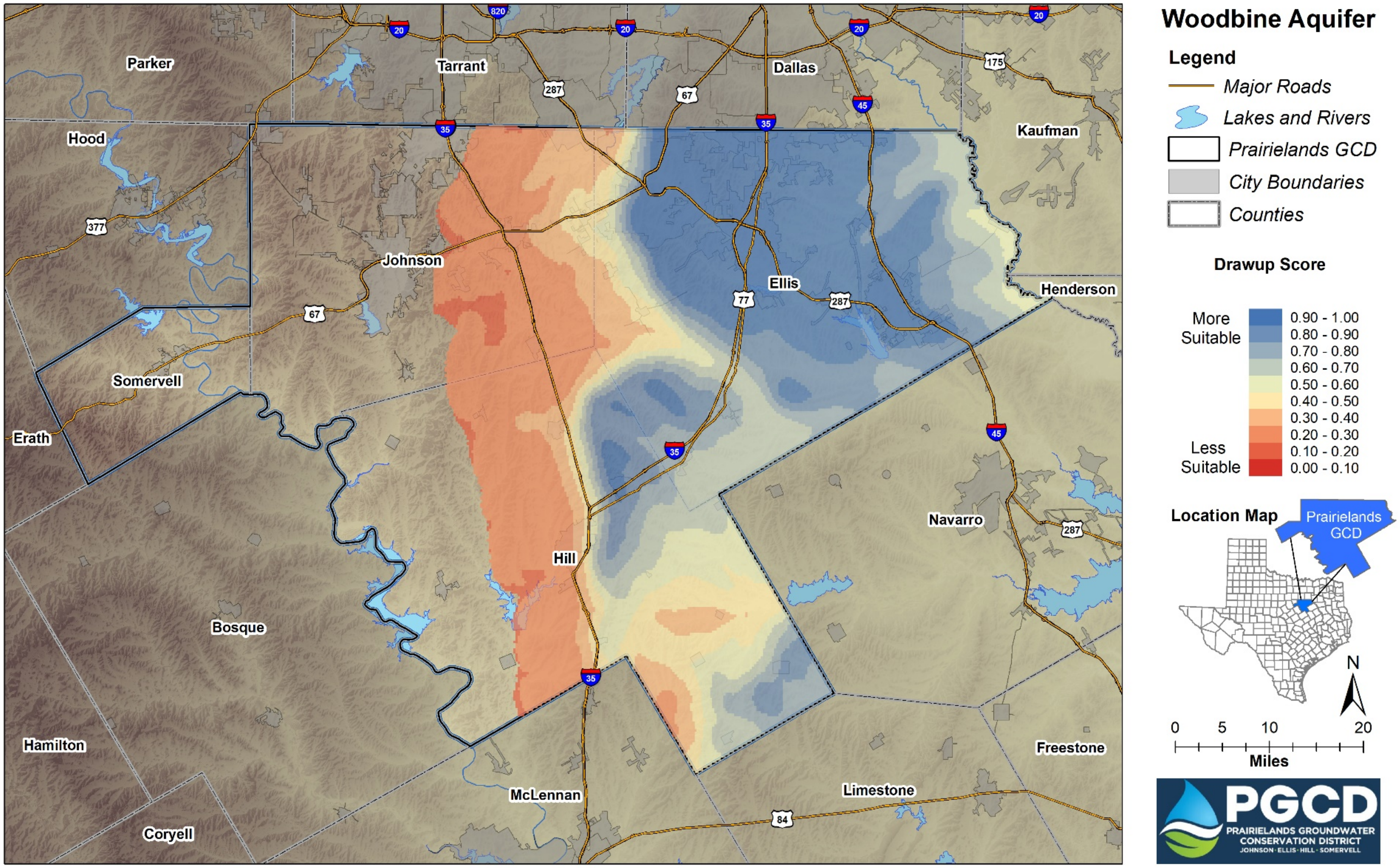
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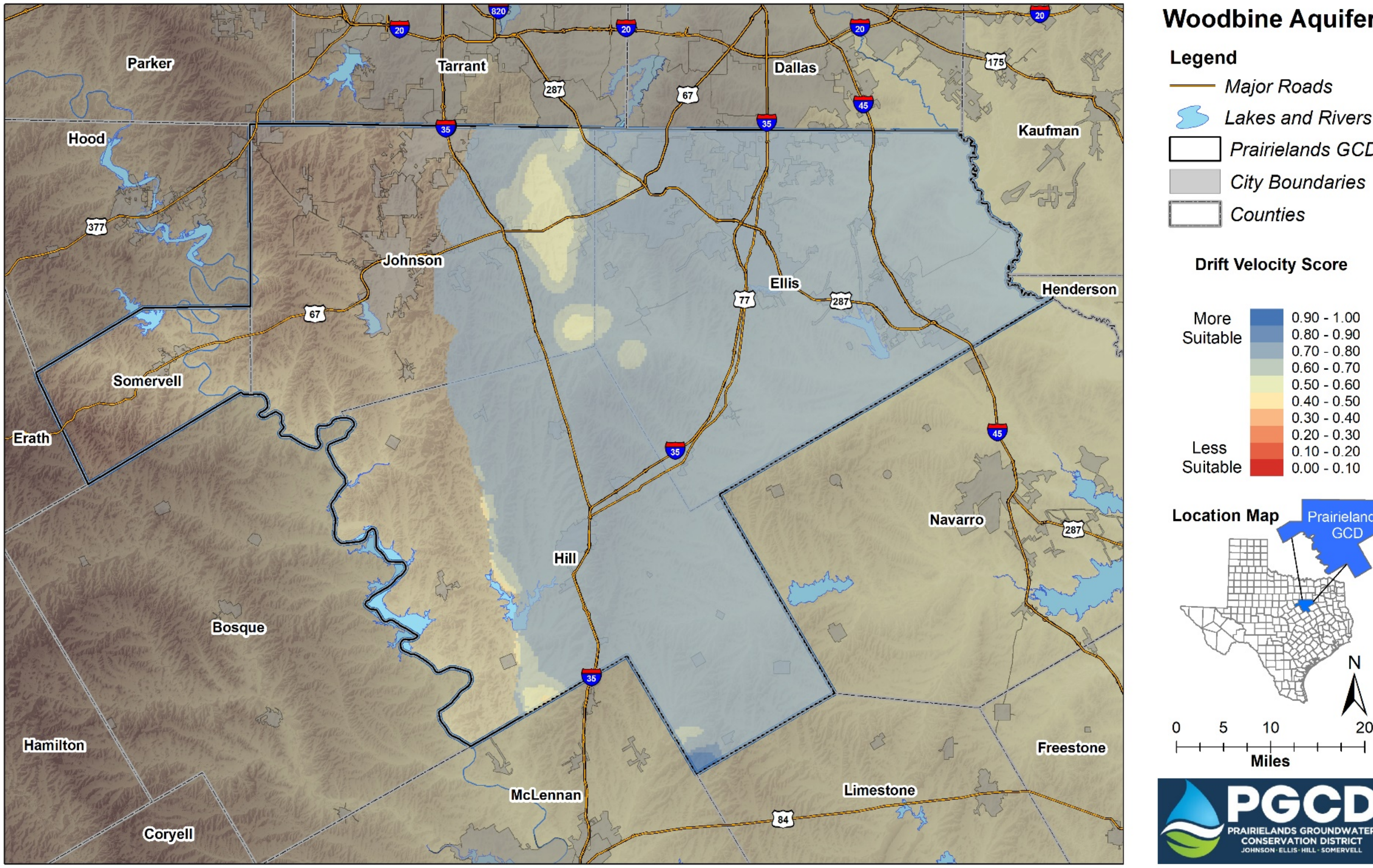
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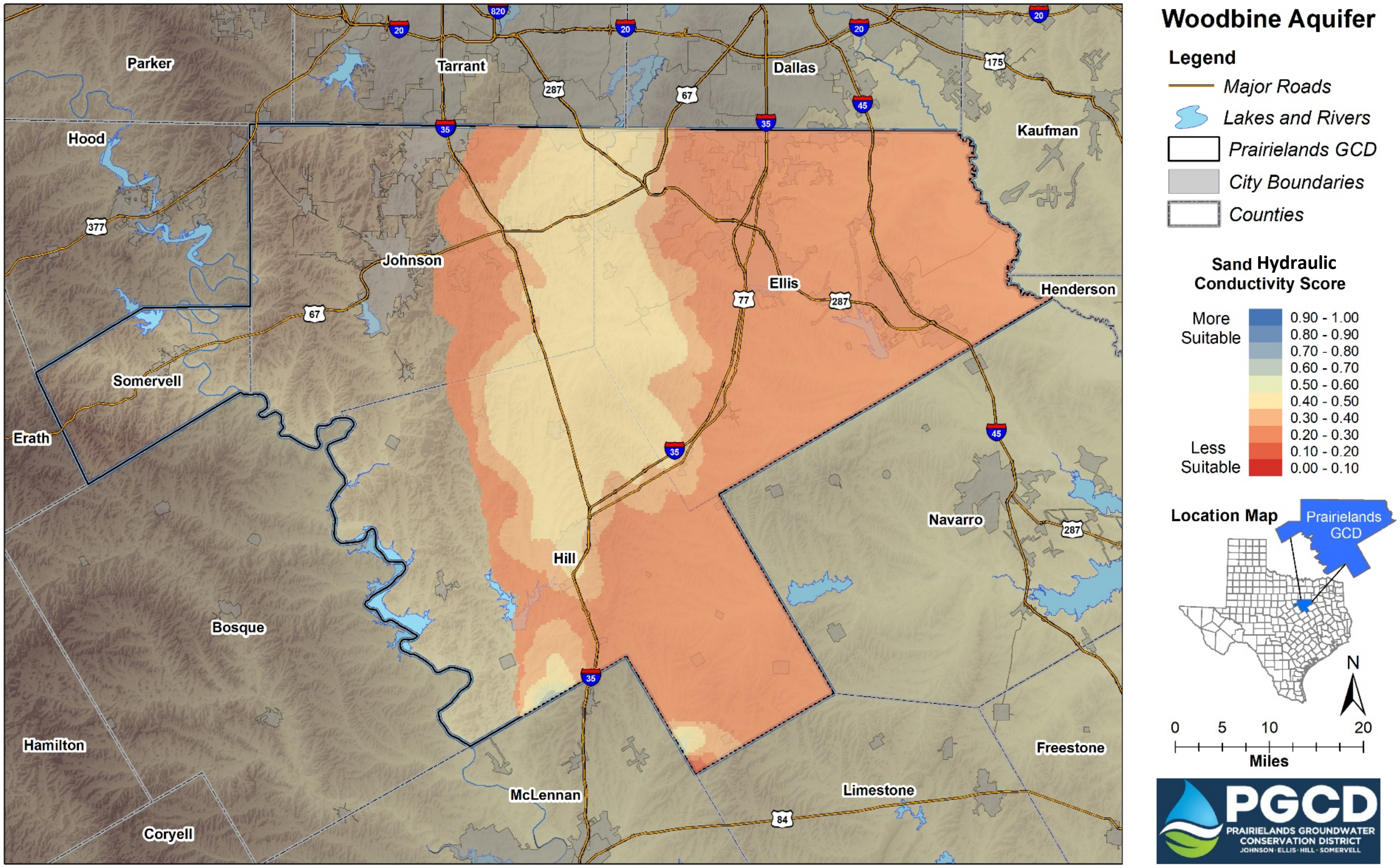
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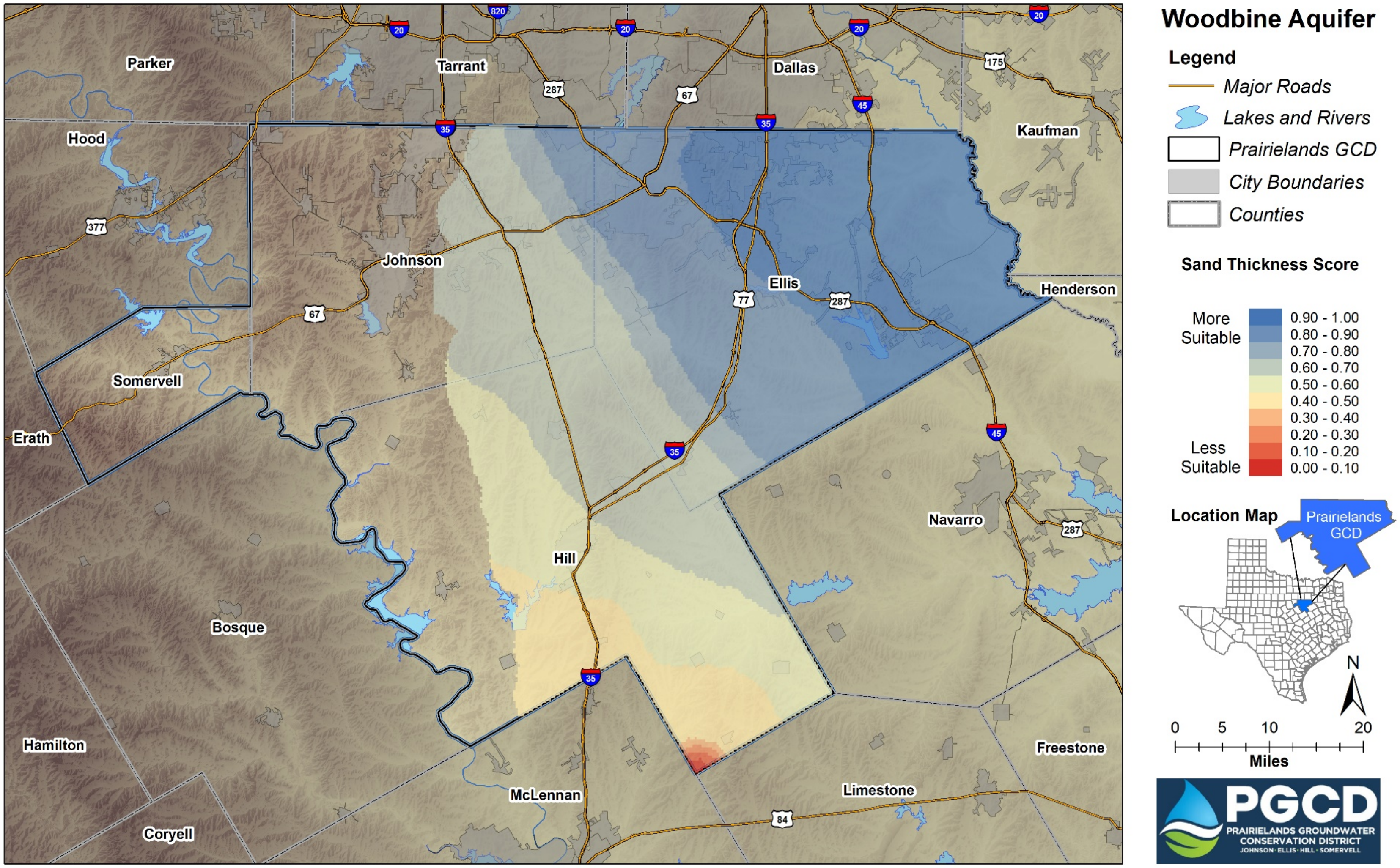
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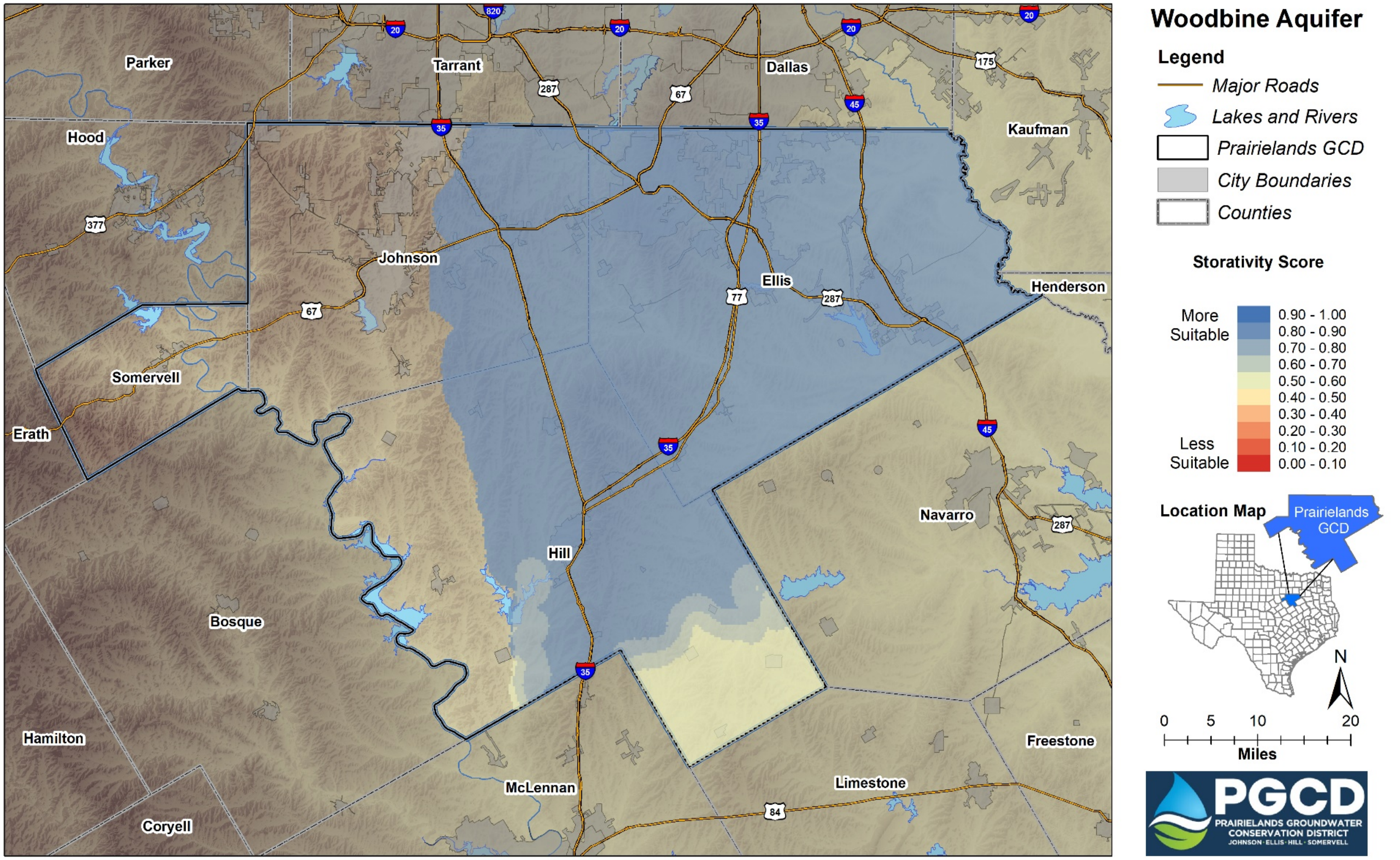
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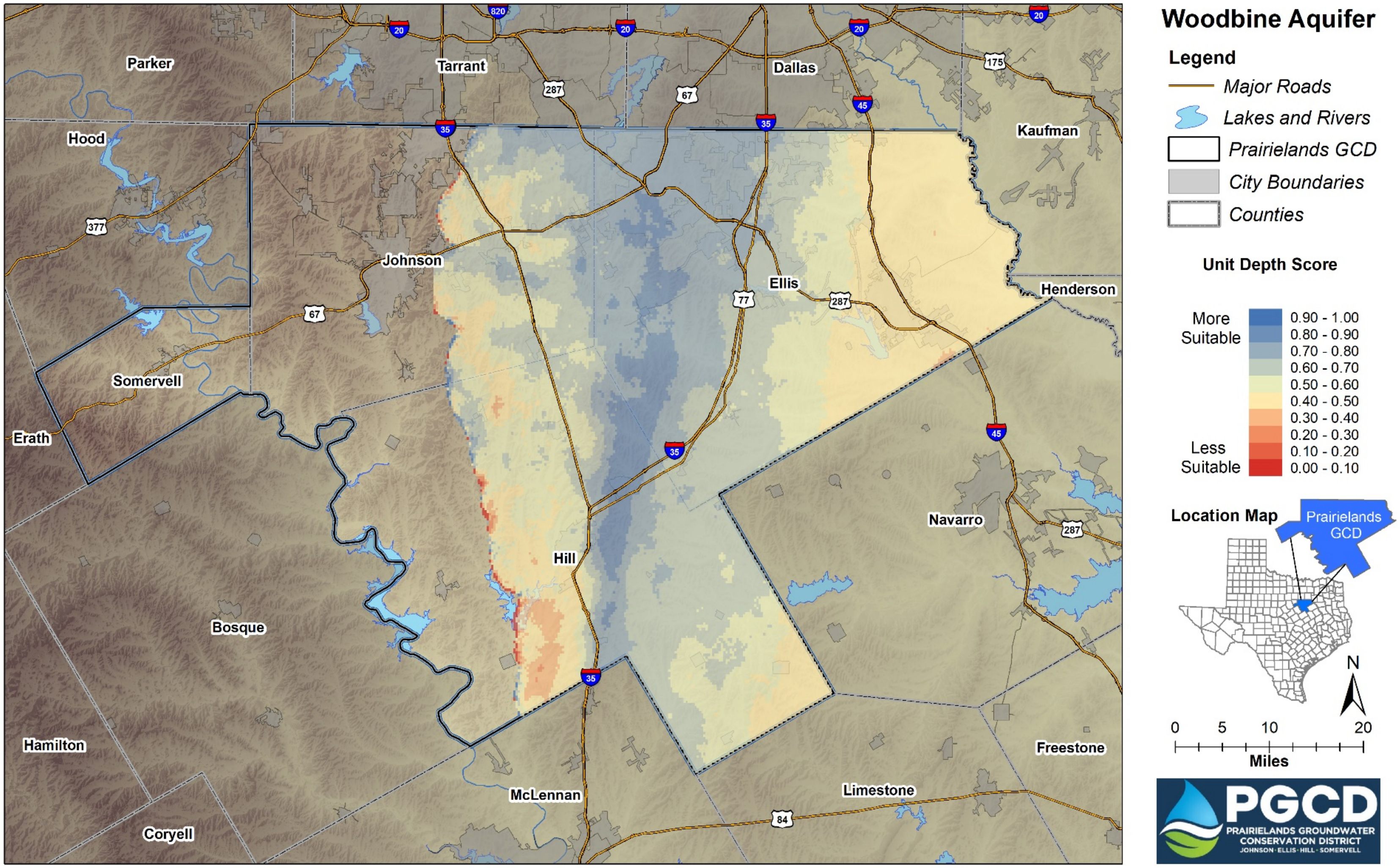
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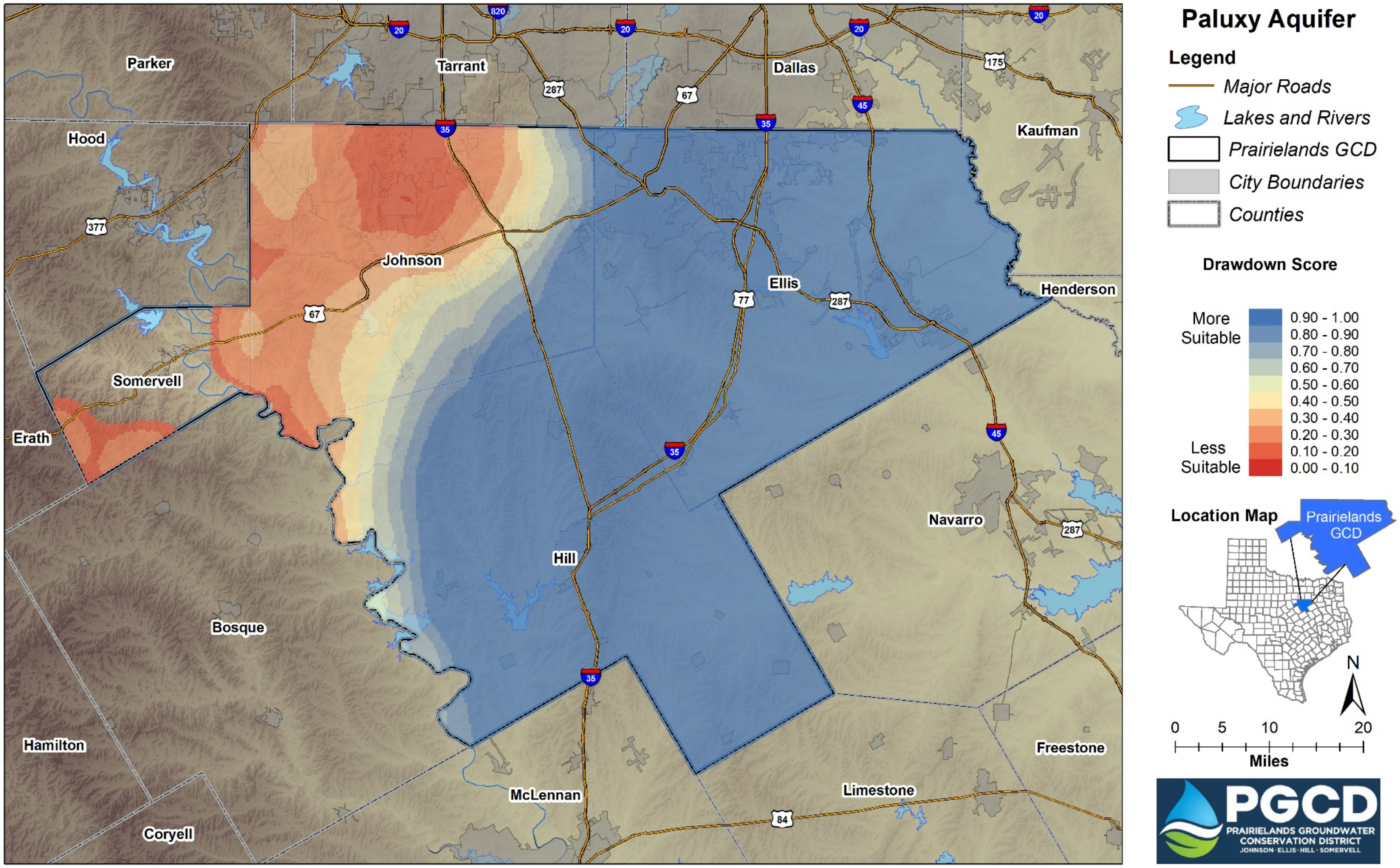
APPENDIX B:
PALUXY ASR - HYDROGEOLOGIC PARAMETER SCORES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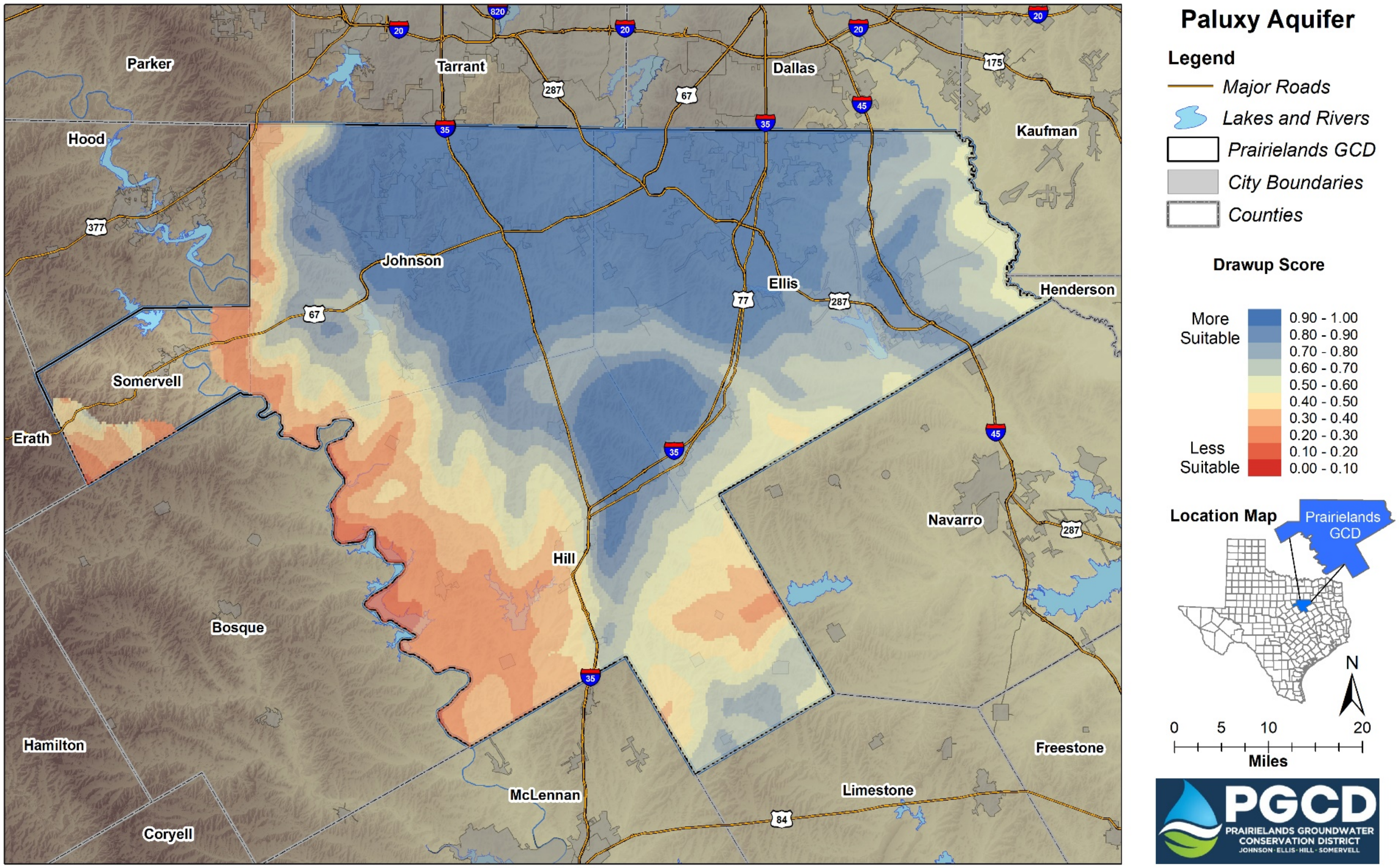
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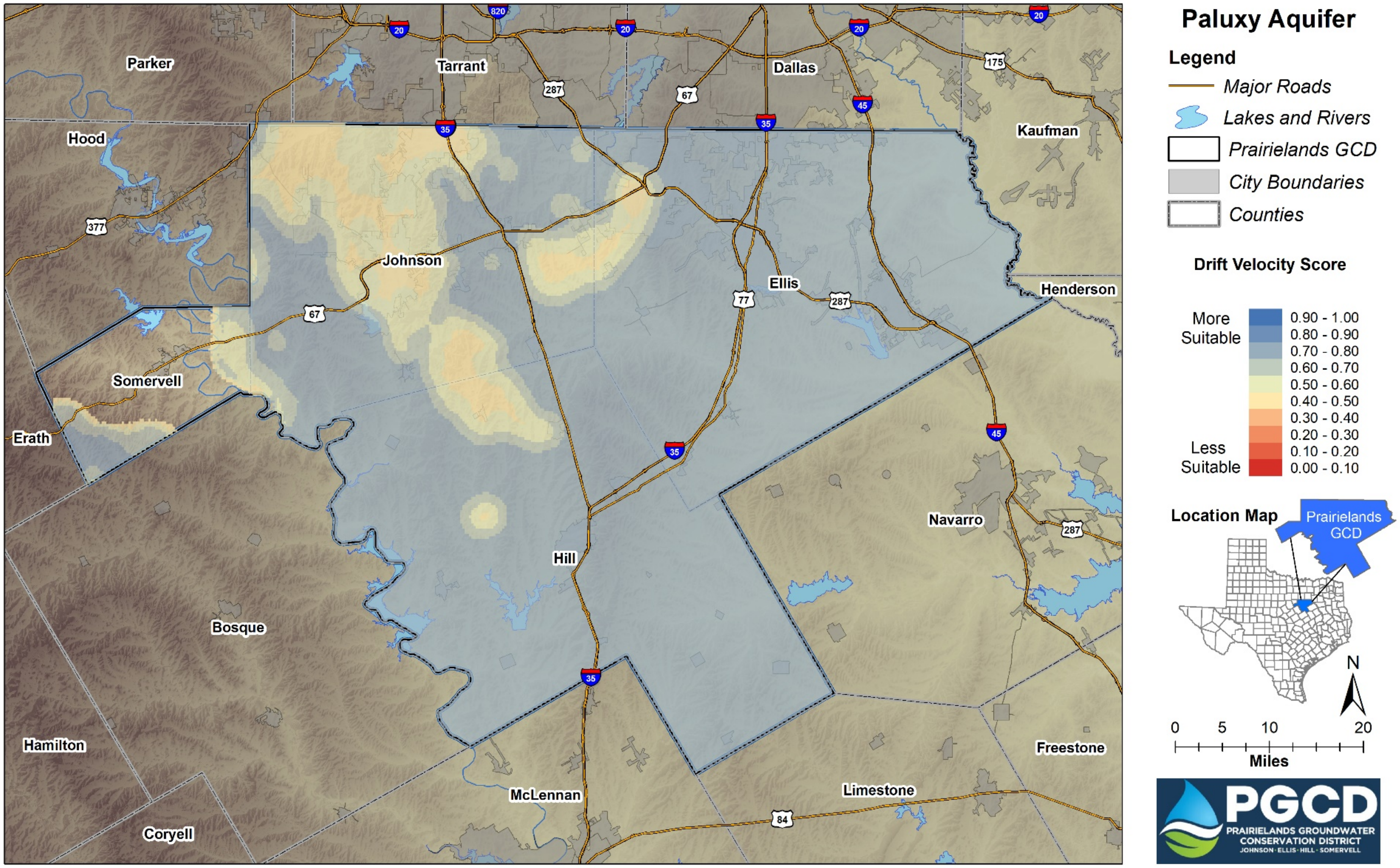
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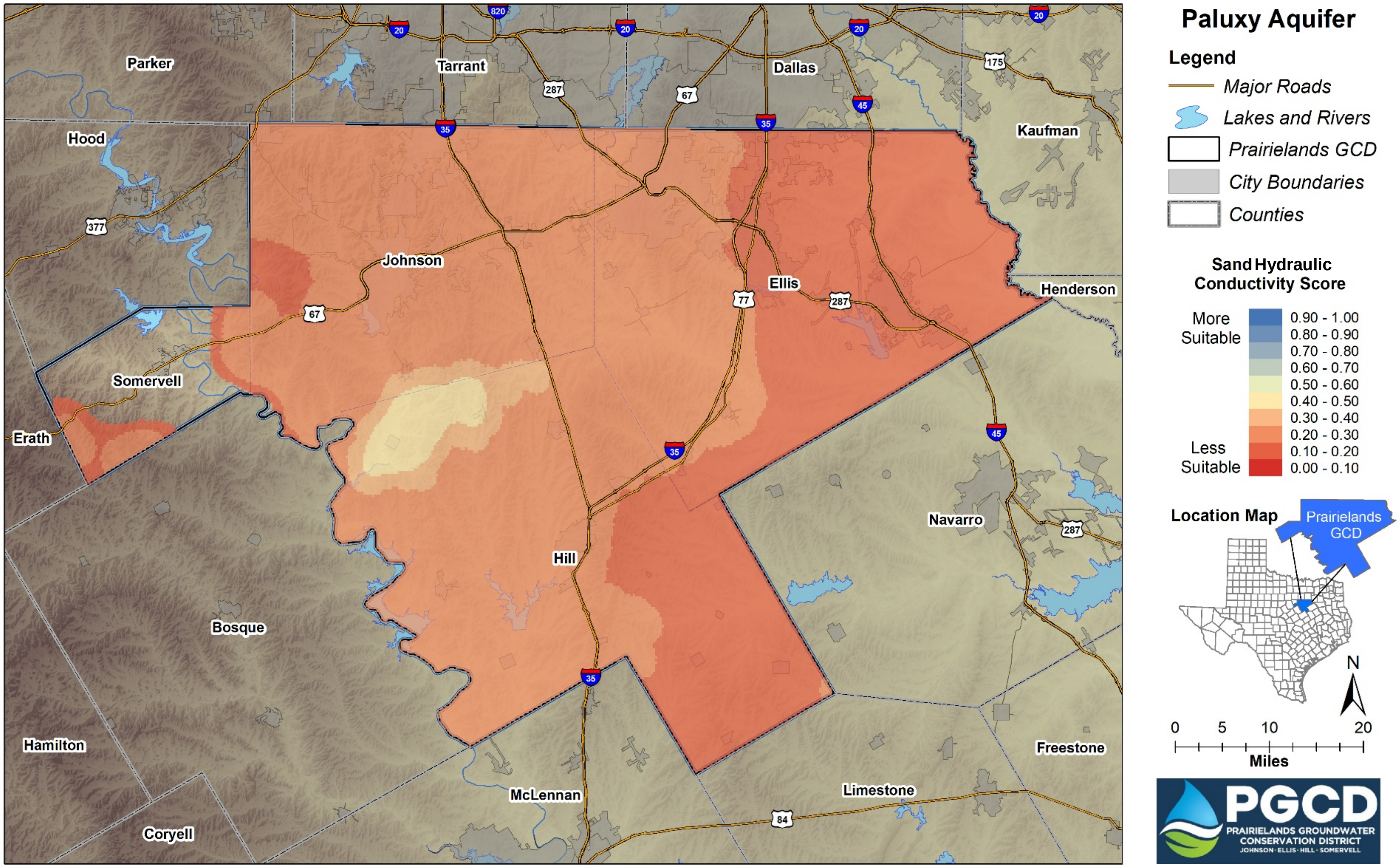
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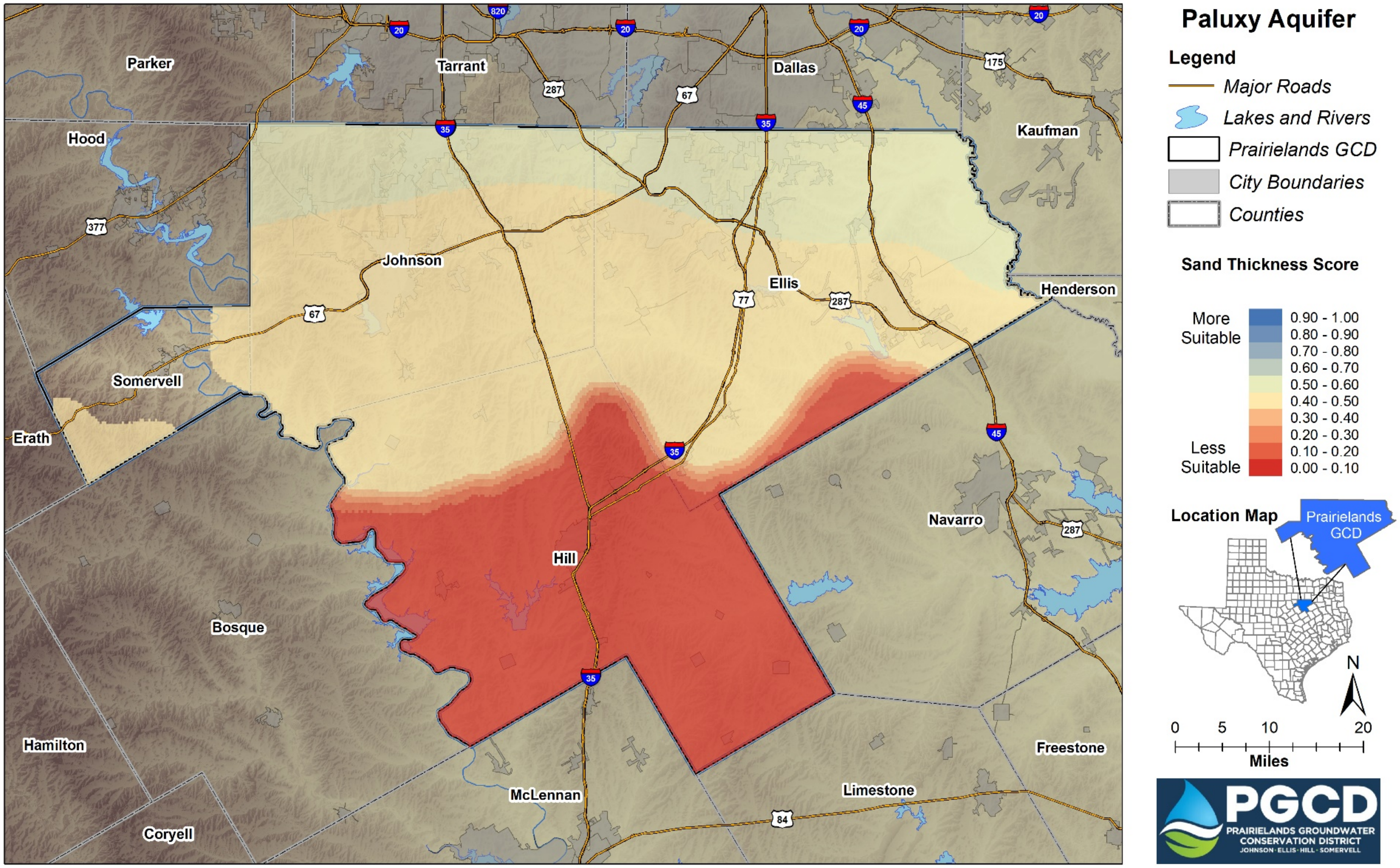
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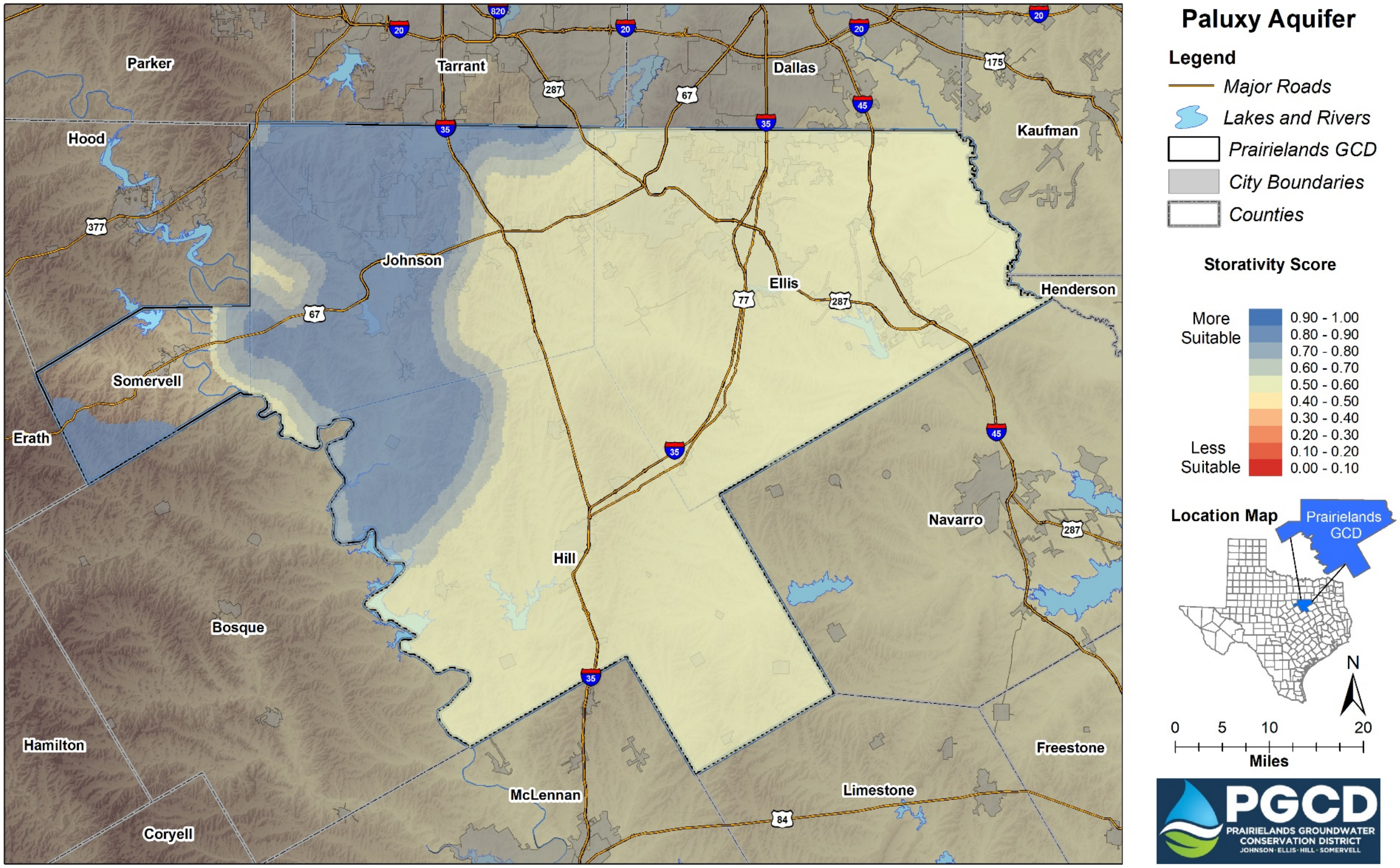
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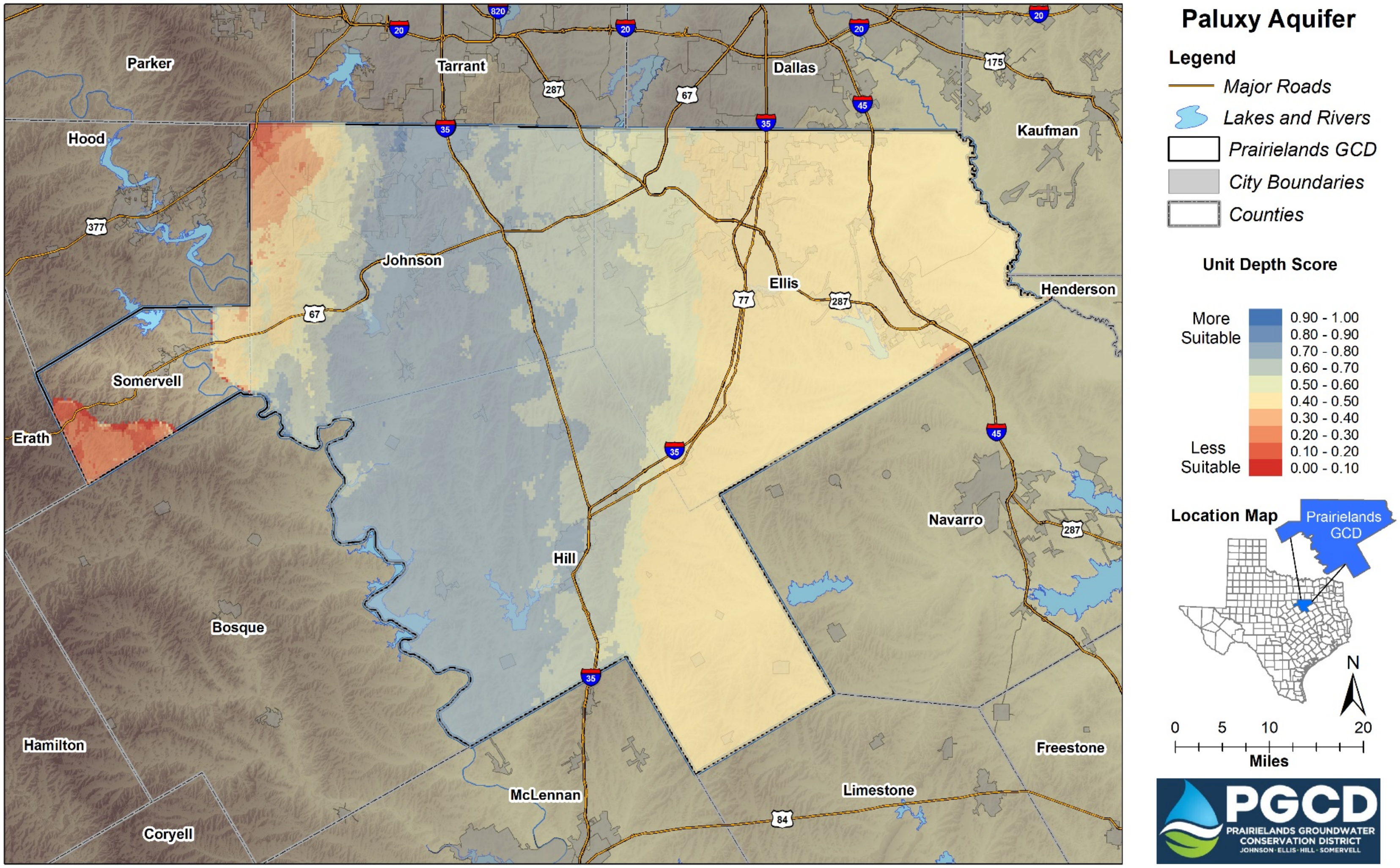
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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Unit Depth Score
More Suitable
Less Suitable
0.90 - 1.00
0.80 - 0.90
0.70 - 0.80
0.60 - 0.70
0.50 - 0.60
0.40 - 0.50
0.30 - 0.40
0.20 - 0.30
0.10 - 0.20
0.00 - 0.10
Location Map
Prairielands GCD
N
0 5 10 20
Miles
Parker
Tarrant
Dallas
Kaufman
Hood
Johnson
Ellis
Henderson
Somervell
Erath
Navarro
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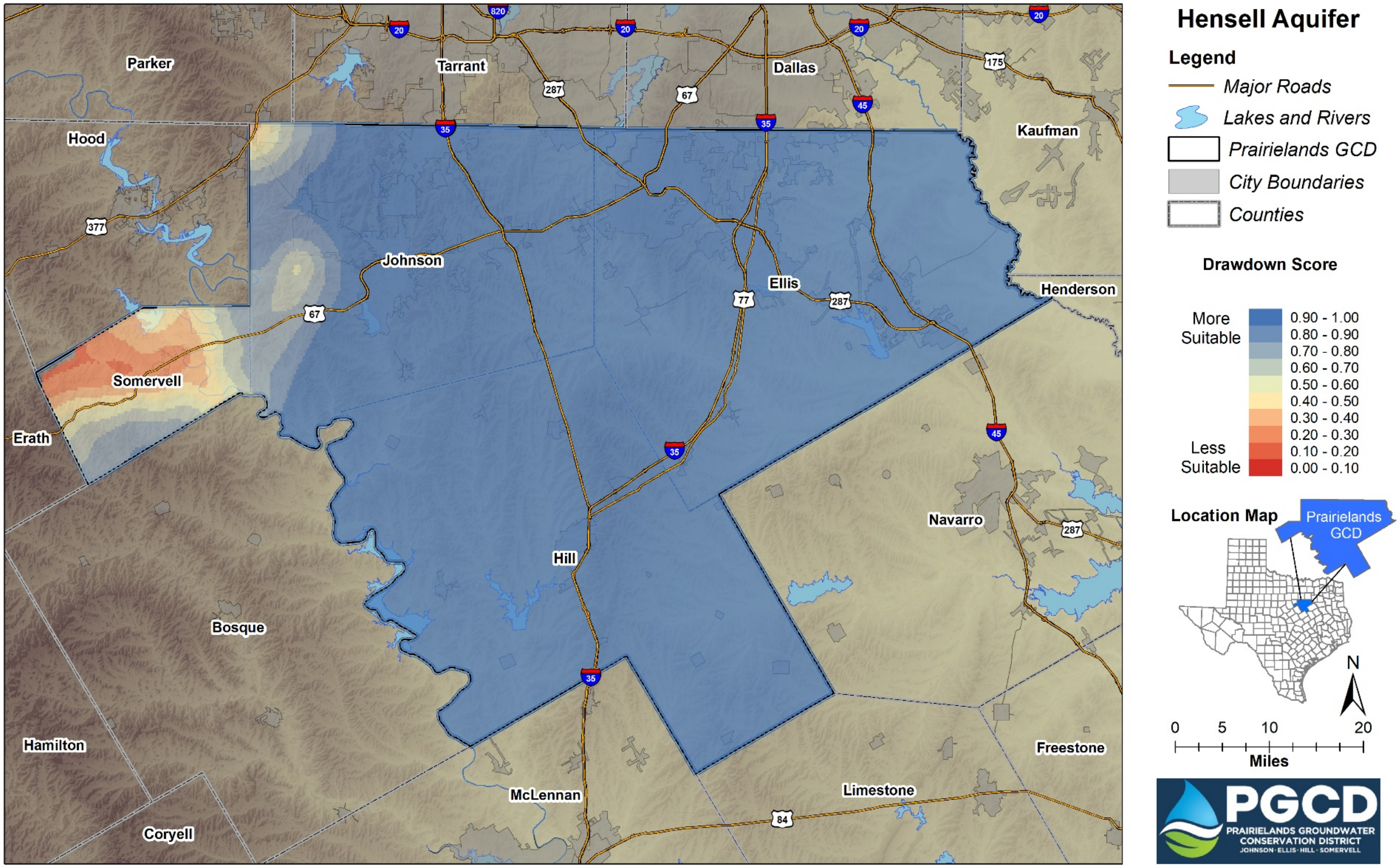
Hamilton
McLennan
Limestone
Freestone
Coryell

APPENDIX C:
HENSELL ASR - HYDROGEOLOGIC PARAMETER SCORES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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Drawdown Score
More Suitable
Less Suitable
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0.70 - 0.80
0.60 - 0.70
0.50 - 0.60
0.40 - 0.50
0.30 - 0.40
0.20 - 0.30
0.10 - 0.20
0.00 - 0.10
Location Map
Prairielands GCD
N
0 5 10 20
Miles
Parker
Tarrant
Dallas
Kaufman
Hood
Johnson
Ellis
Henderson
Somervell
Erath
Navarro
Hill
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McLennan
Limestone
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Coryell
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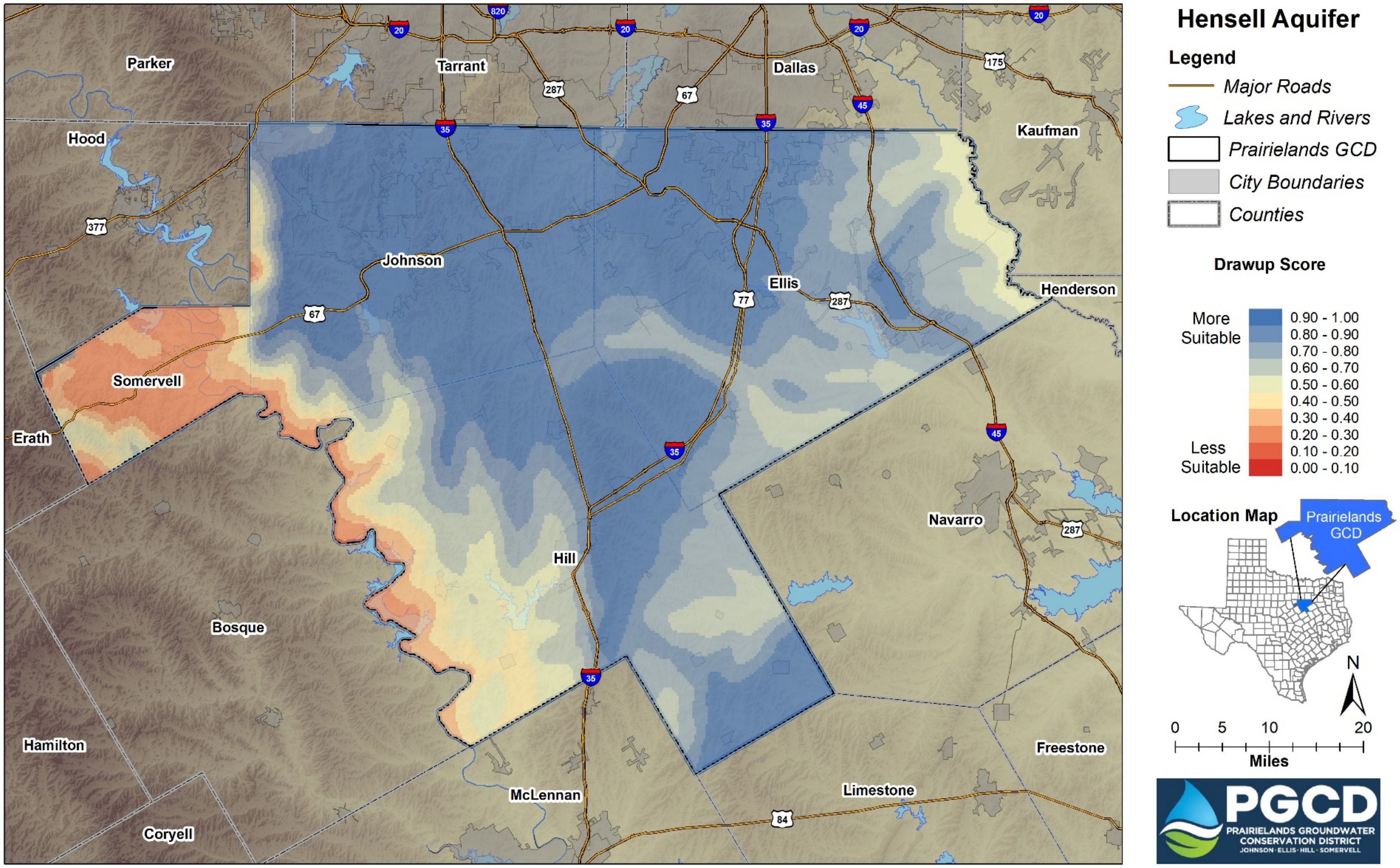
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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Drawup Score
More Suitable
Less Suitable
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0.70 - 0.80
0.60 - 0.70
0.50 - 0.60
0.40 - 0.50
0.30 - 0.40
0.20 - 0.30
0.10 - 0.20
0.00 - 0.10
Location Map
Prairielands GCD
N
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20
Miles
Parker
Tarrant
Dallas
Kaufman
Hood
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Henderson
Somervell
Erath
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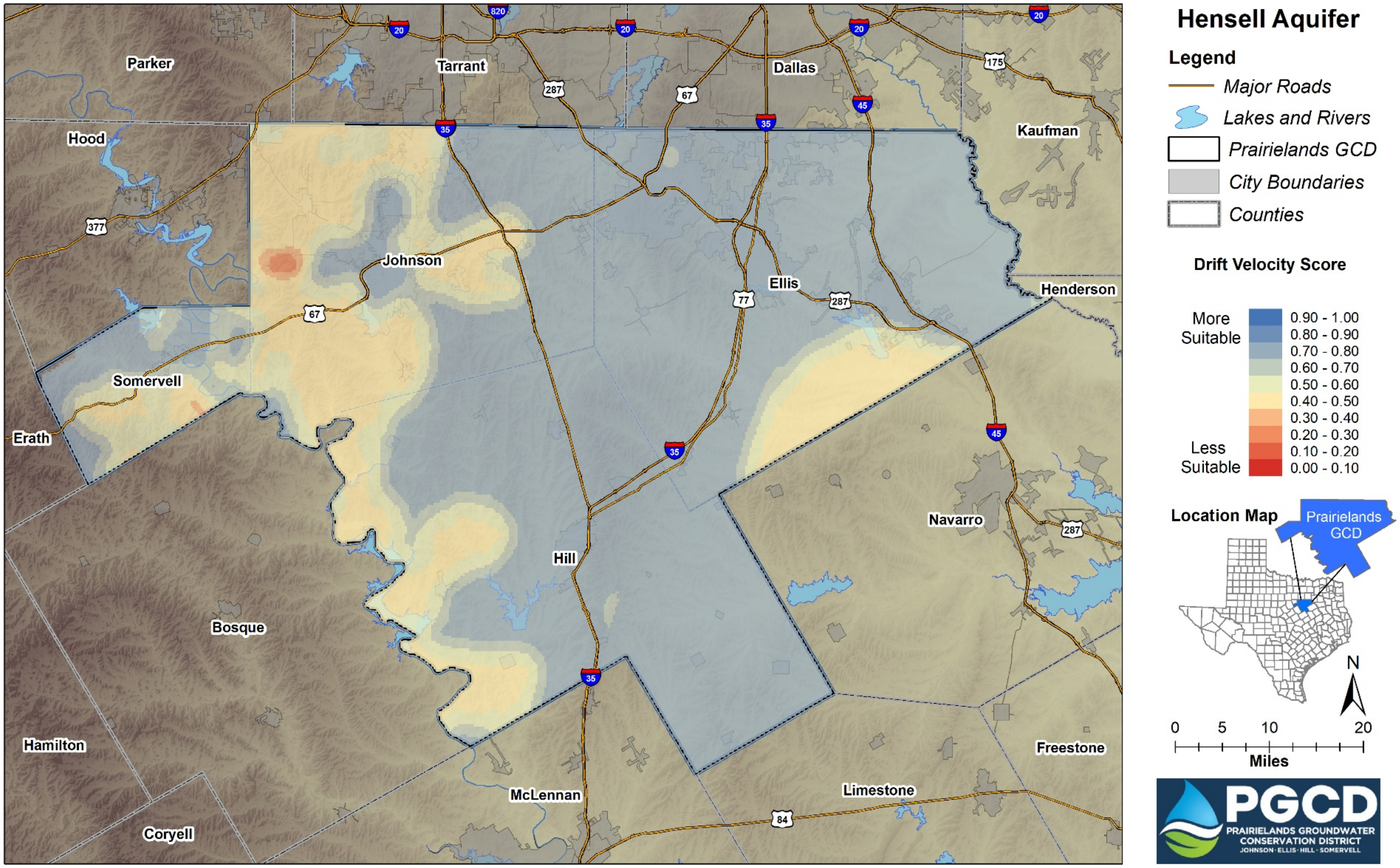
Hamilton
McLennan
Limestone
Freestone
Coryell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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Drift Velocity Score
More Suitable
Less Suitable
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0.80 - 0.90
0.70 - 0.80
0.60 - 0.70
0.50 - 0.60
0.40 - 0.50
0.30 - 0.40
0.20 - 0.30
0.10 - 0.20
0.00 - 0.10
Location Map
Prairielands GCD
N
0 5 10 20
Miles
Parker
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Dallas
Kaufman
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Somervell
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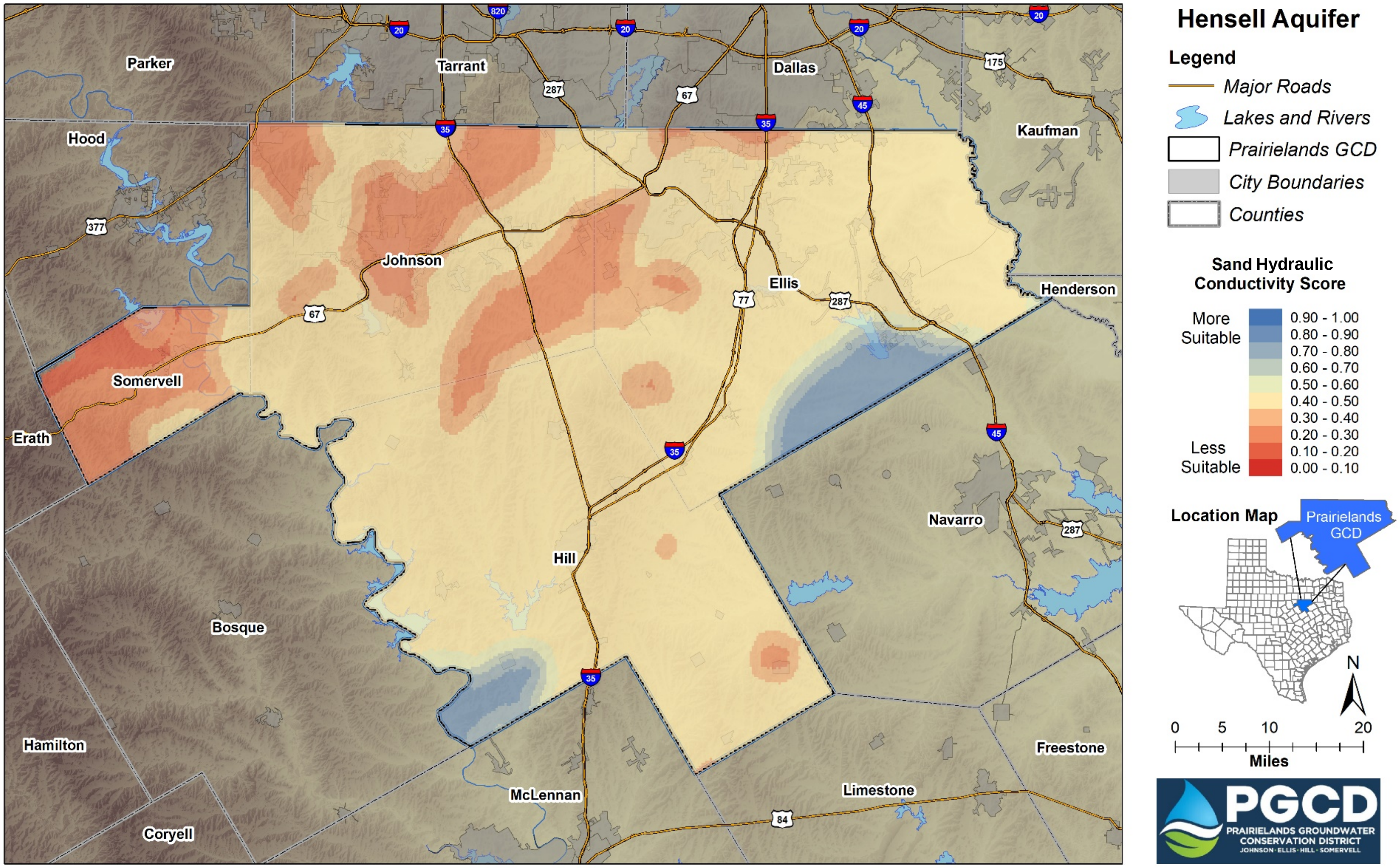
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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Sand Hydraulic Conductivity Score
More Suitable
Less Suitable
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0.80 - 0.90
0.70 - 0.80
0.60 - 0.70
0.50 - 0.60
0.40 - 0.50
0.30 - 0.40
0.20 - 0.30
0.10 - 0.20
0.00 - 0.10
Location Map
Prairielands GCD
N
0 5 10 20
Miles
Parker
Tarrant
Dallas
Kaufman
Hood
Johnson
Ellis
Henderson
Somervell
Erath
Navarro
Hill
Bosque
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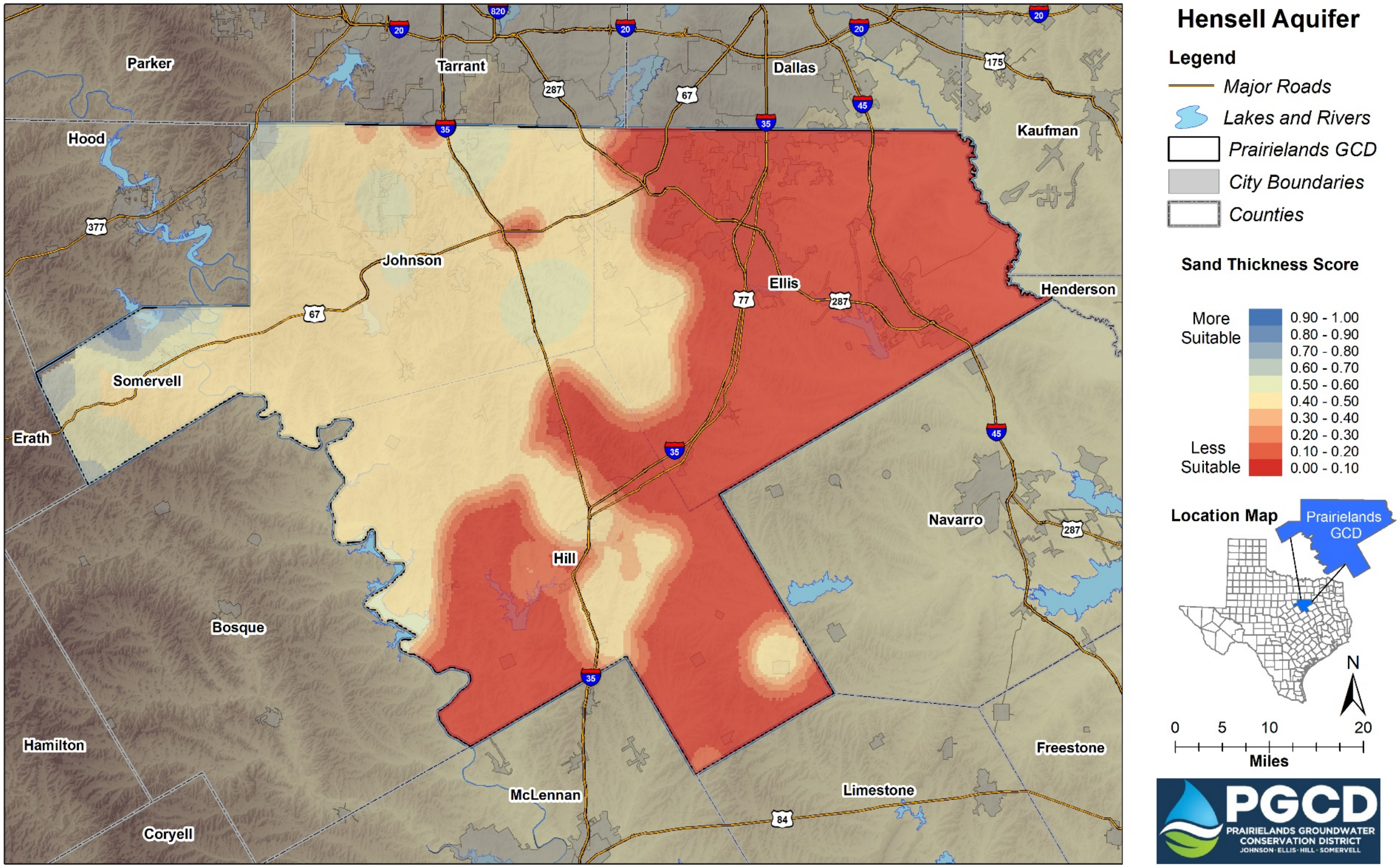
Freestone
Coryell
PGCD
PRAIRIELANDS GROUNDWATER CONSERVATION DISTRICT
JOHNSON · ELLIS · HILL · SOMERVELL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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Sand Thickness Score
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0.20 - 0.30
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Location Map
Prairielands GCD
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0 5 10 20
Miles
Parker
Tarrant
Dallas
Kaufman
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Johnson
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Somervell
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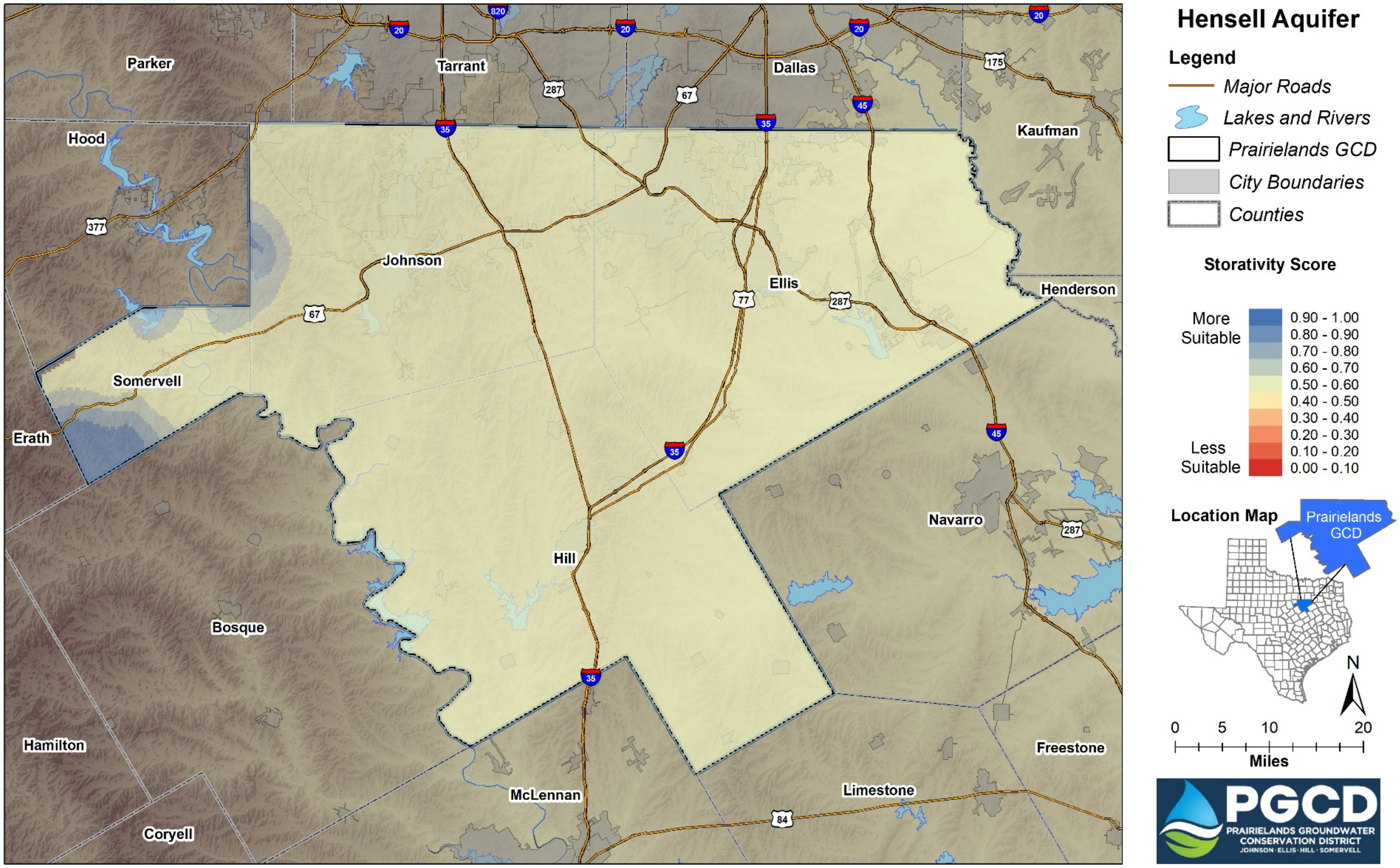
Hamilton
McLennan
Limestone
Freestone
Coryell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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Storativity Score
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Less Suitable
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0.80 - 0.90
0.70 - 0.80
0.60 - 0.70
0.50 - 0.60
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0.00 - 0.10
Location Map
Prairielands GCD
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Miles
Parker
Tarrant
Dallas
Kaufman
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Freestone
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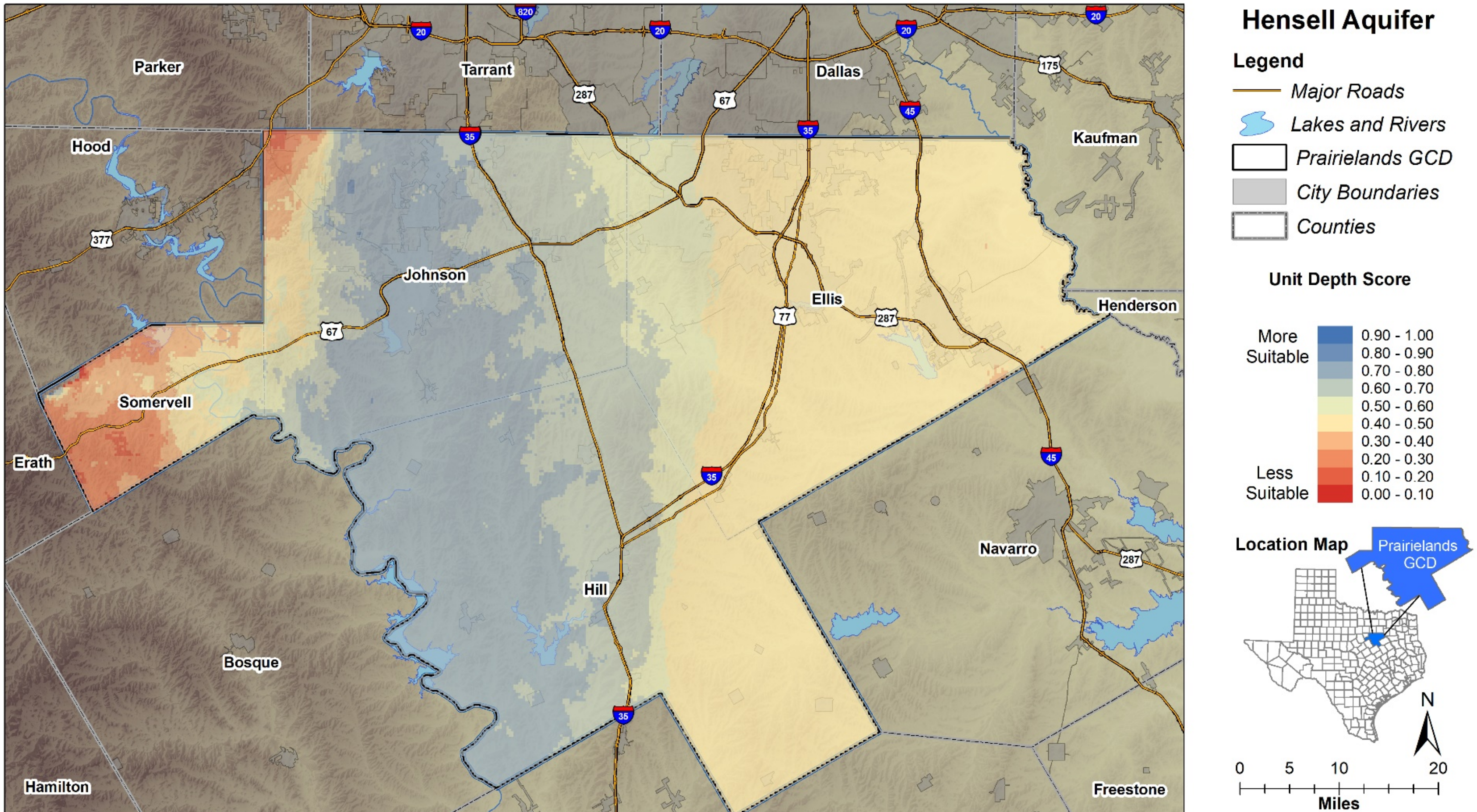
Coryell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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Unit Depth Score
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Less Suitable
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Location Map
Prairielands GCD
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Miles
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Kaufman
Johnson
Ellis
Henderson
Somervell
Erath
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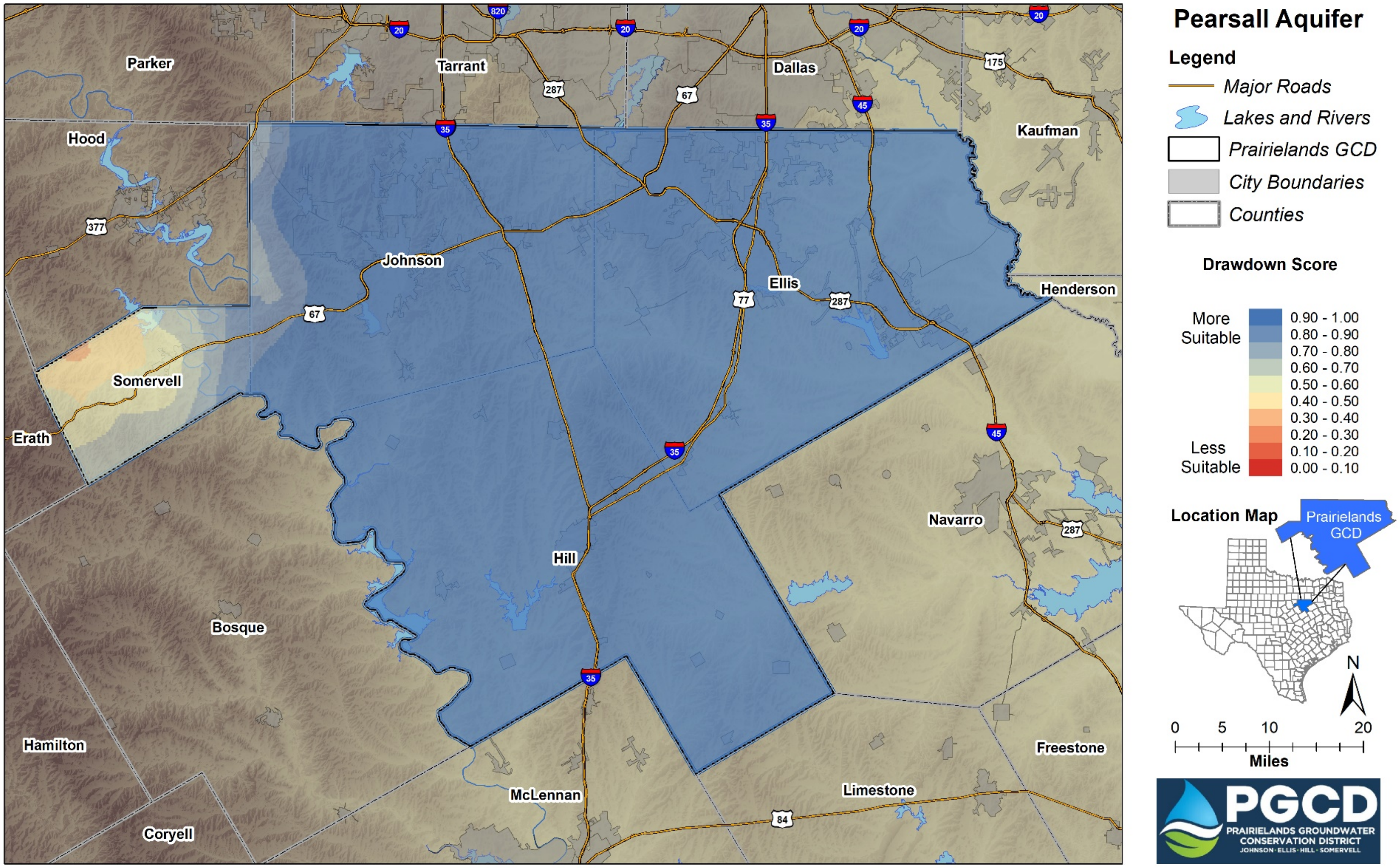
Freestone
Limestone
McLennan
Coryell

APPENDIX D:
PEARSALL ASR - HYDROGEOLOGIC PARAMETER SCORES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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Drawdown Score
More Suitable
Less Suitable
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0.80 - 0.90
0.70 - 0.80
0.60 - 0.70
0.50 - 0.60
0.40 - 0.50
0.30 - 0.40
0.20 - 0.30
0.10 - 0.20
0.00 - 0.10
Location Map
Prairielands GCD
N
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Miles
Parker
Tarrant
Dallas
Hood
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Somervell
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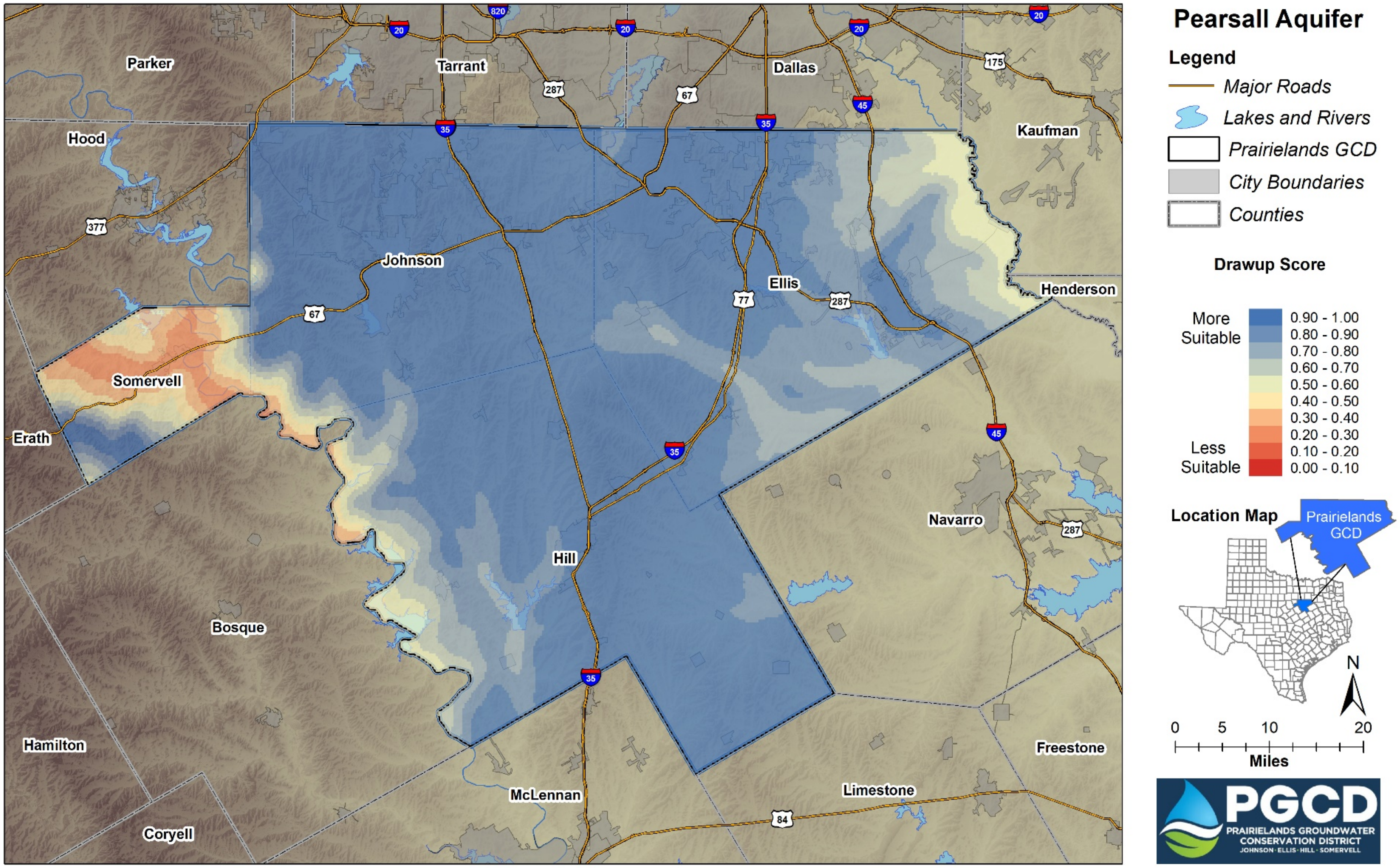
Limestone
Freestone
Coryell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Erath
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Hill
Bosque
Hamilton
Freestone
McLennan
Limestone
Coryell
Pearsall Aquifer
Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Drawup Score
More Suitable
Less Suitable
0.90 - 1.00
0.80 - 0.90
0.70 - 0.80
0.60 - 0.70
0.50 - 0.60
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0.10 - 0.20
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Location Map
Prairielands GCD
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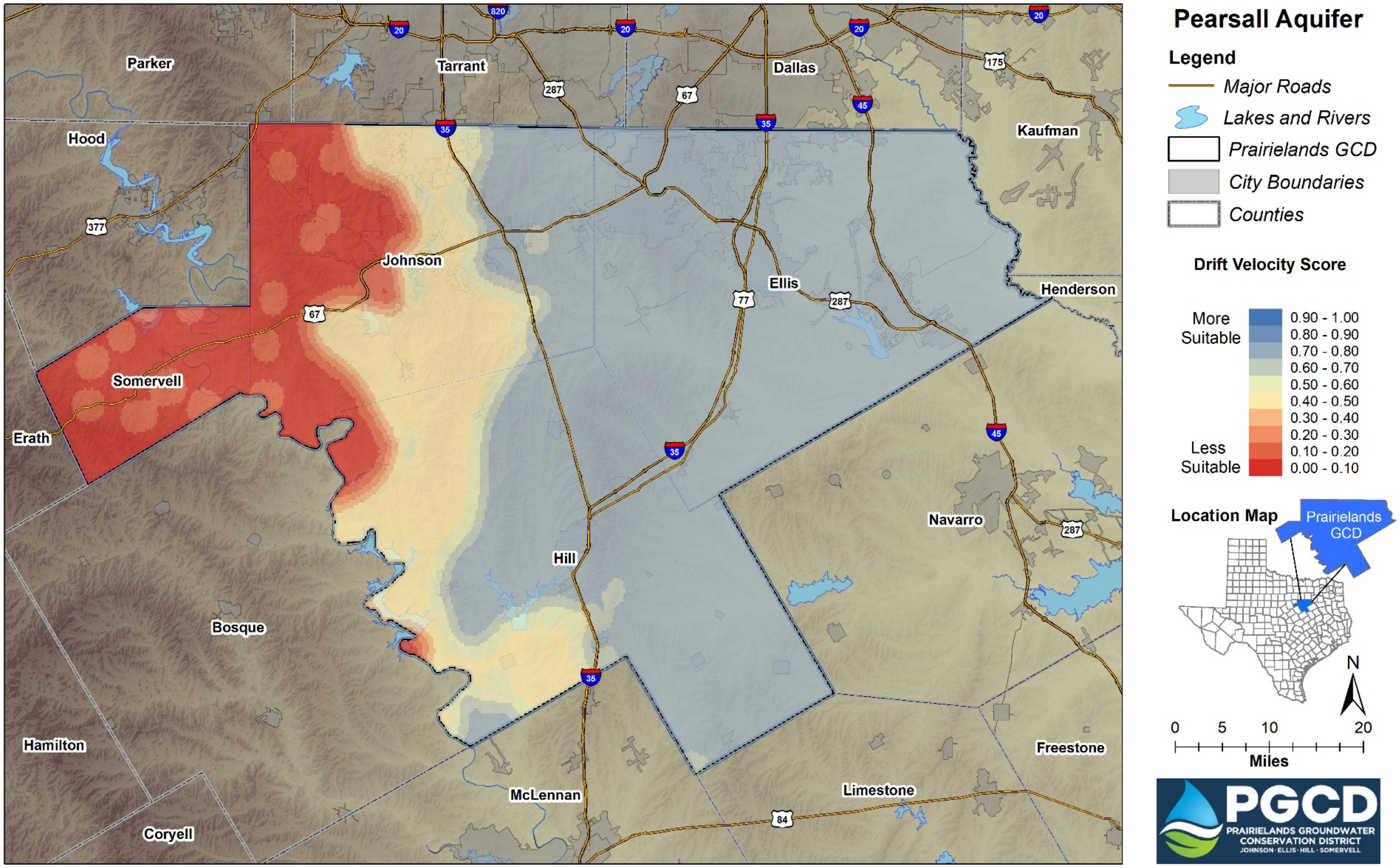
Miles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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Drift Velocity Score
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Less Suitable
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0.70 - 0.80
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Location Map
Prairielands GCD
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Miles
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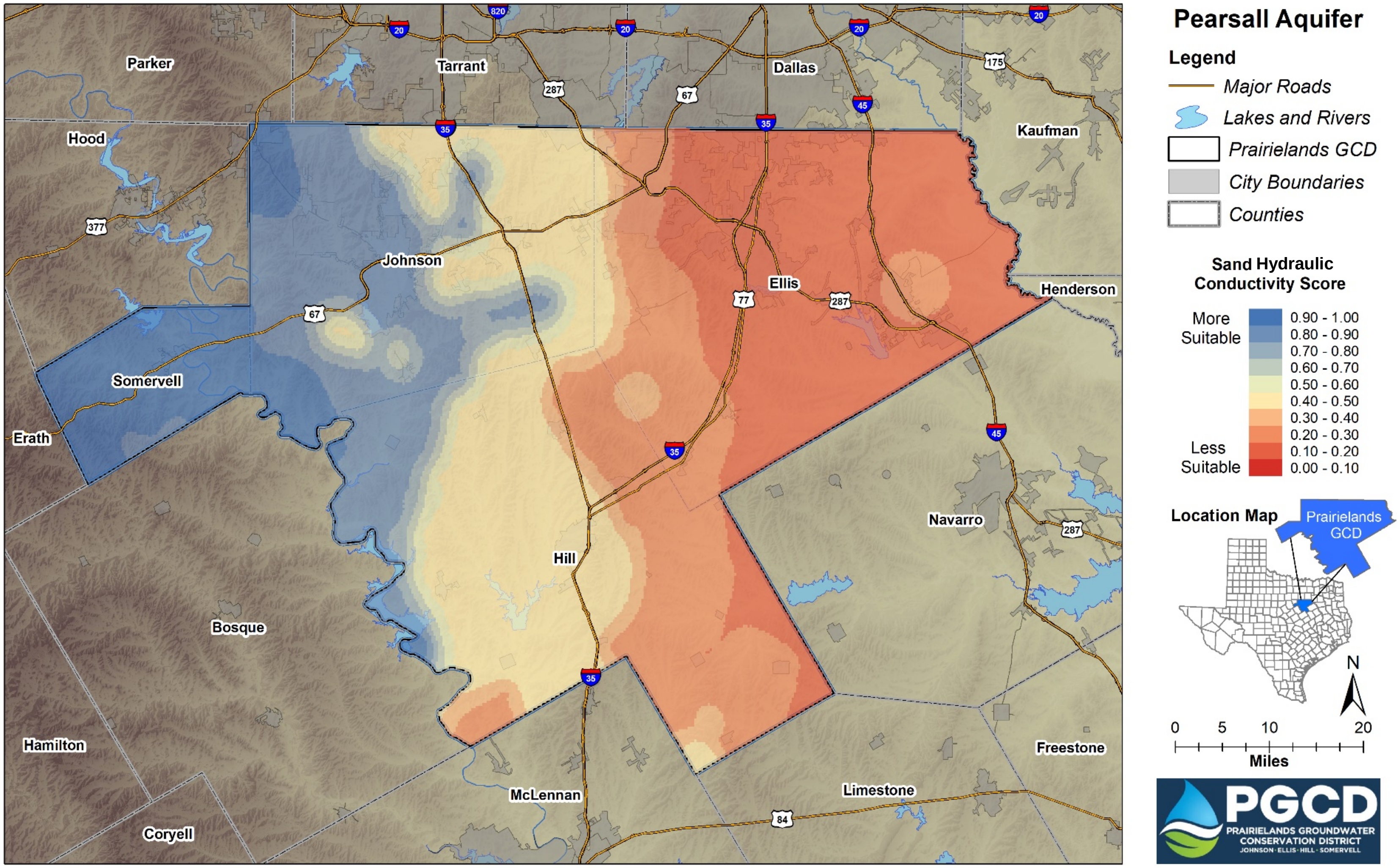
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Legend
Major Roads
Lakes and Rivers
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City Boundaries
Counties
Sand Hydraulic Conductivity Score
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Less Suitable
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Location Map
Prairielands GCD
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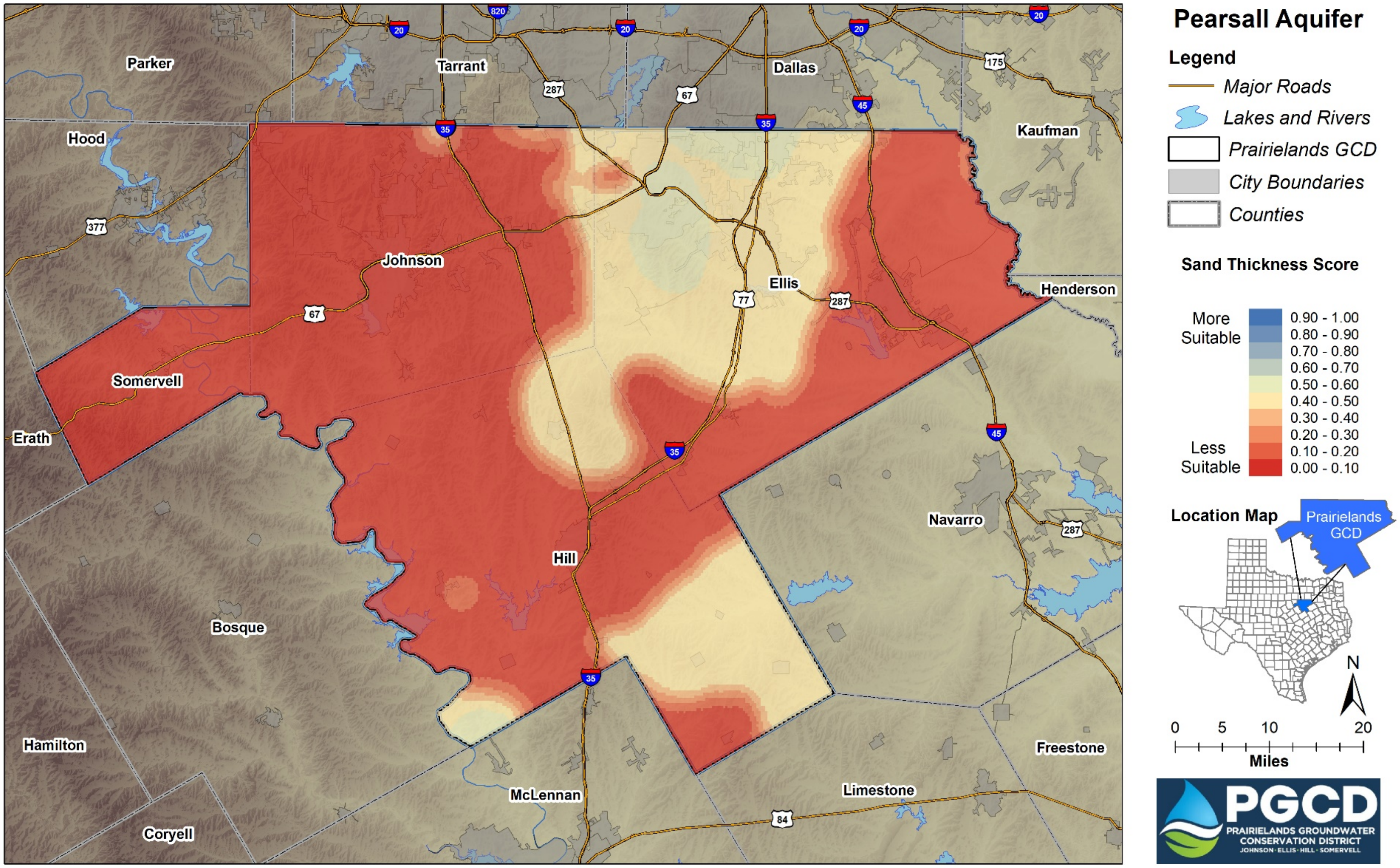
Freestone
Coryell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Legend
Major Roads
Lakes and Rivers
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City Boundaries
Counties
Sand Thickness Score
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Location Map
Prairielands GCD
N
0 5 10 20
Miles
Parker
Tarrant
Dallas
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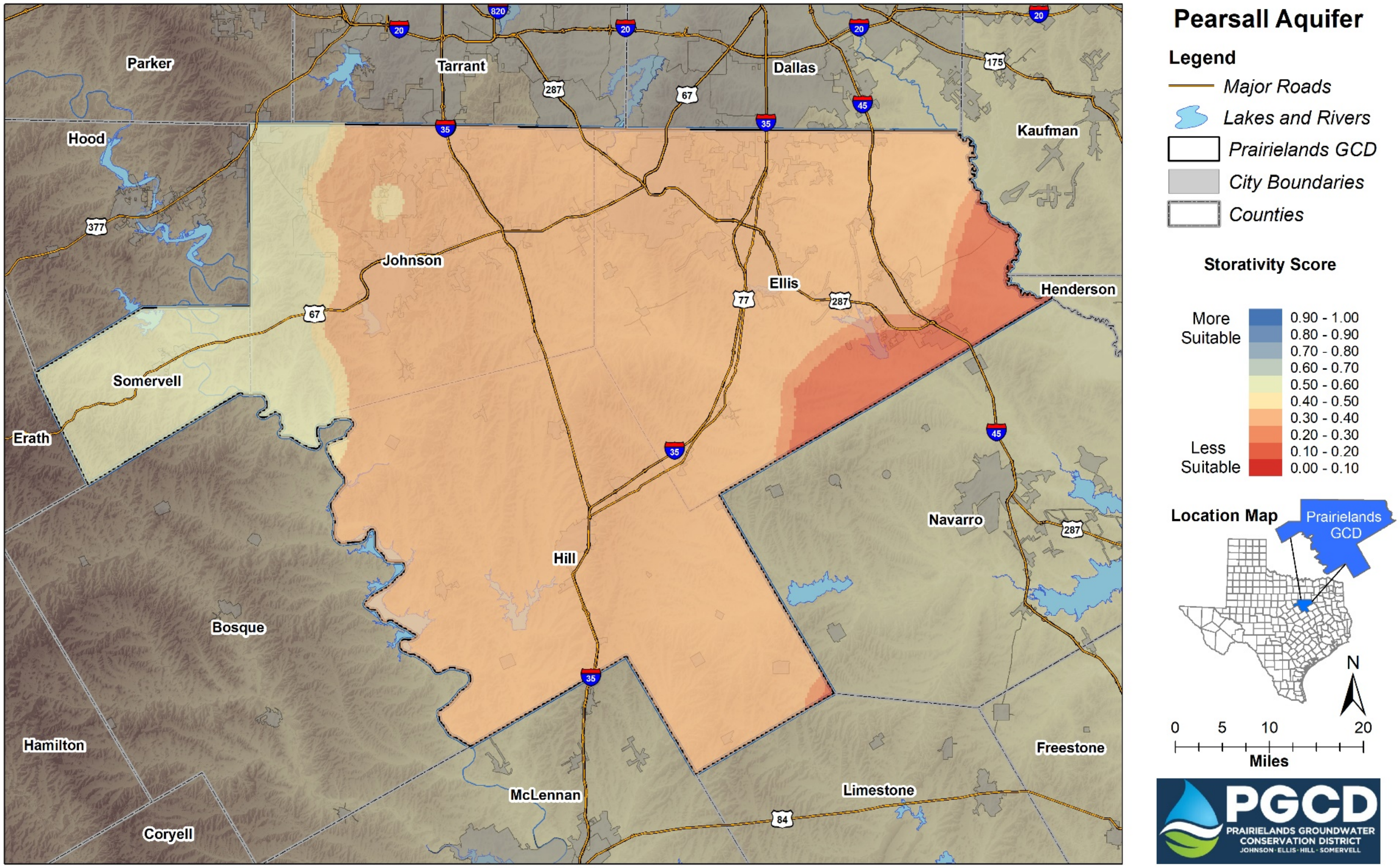
Coryell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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Storativity Score
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0.20 - 0.30
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Location Map
Prairielands GCD
N
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Miles
Parker
Tarrant
Dallas
Kaufman
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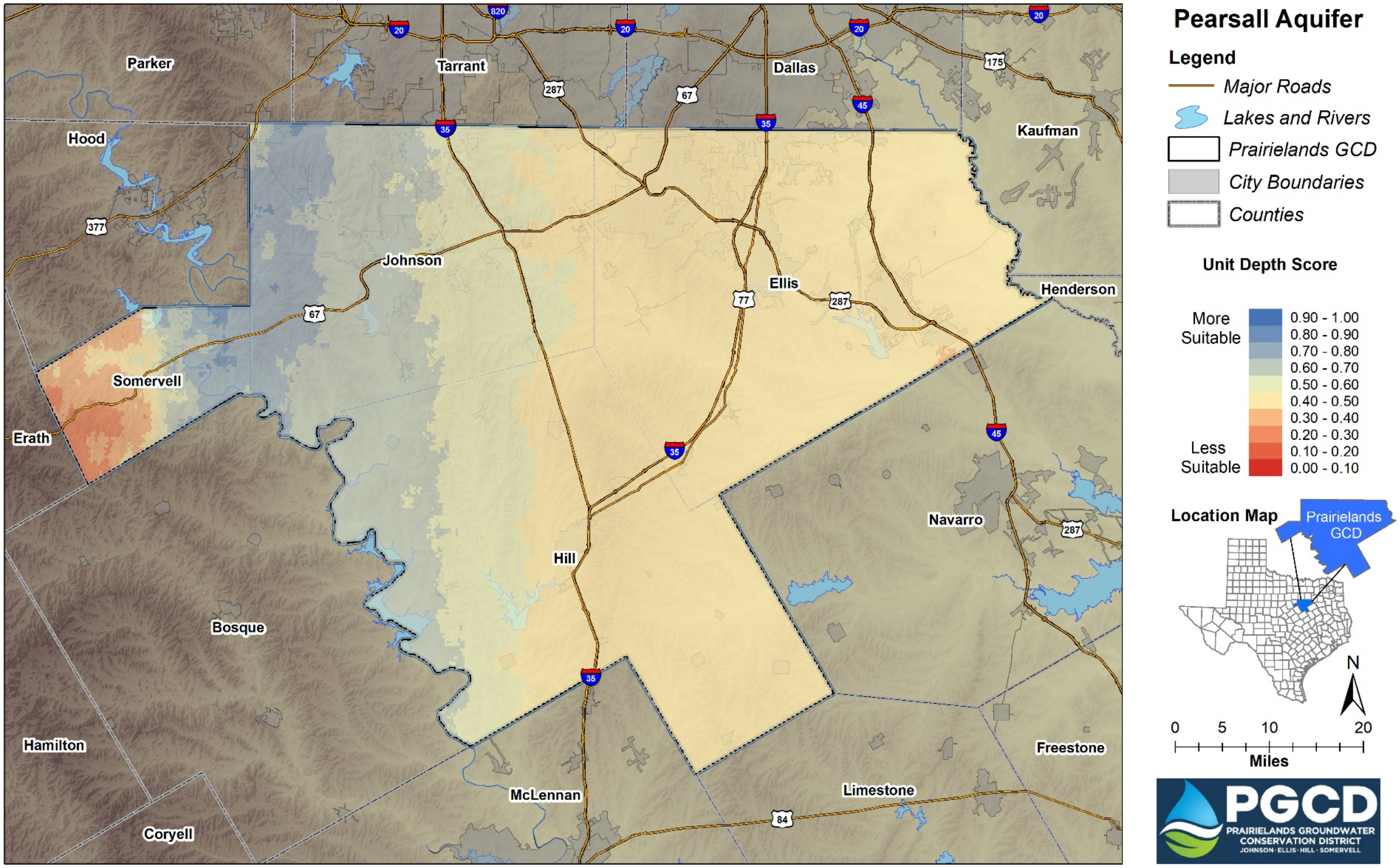
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Limestone
Freestone
Coryell
Pearsall Aquifer
Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Unit Depth Score
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Less Suitable
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Location Map
Prairielands GCD
N
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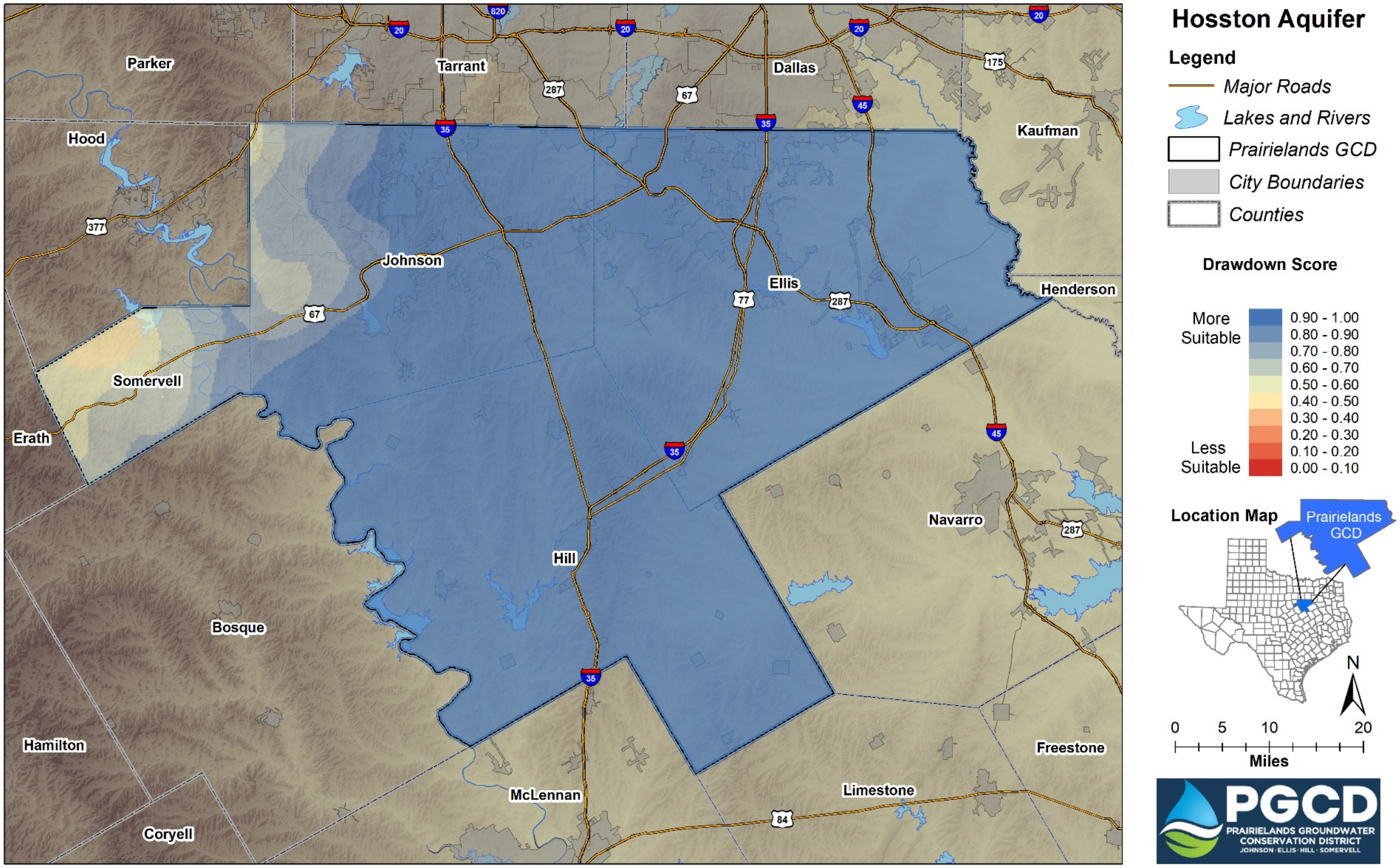
Miles

APPENDIX E:
HOSSTON ASR - HYDROGEOLOGIC PARAMETER SCORES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Freestone
Limestone
McLennan
Coryell
Hosston Aquifer
Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Drawdown Score
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Less Suitable
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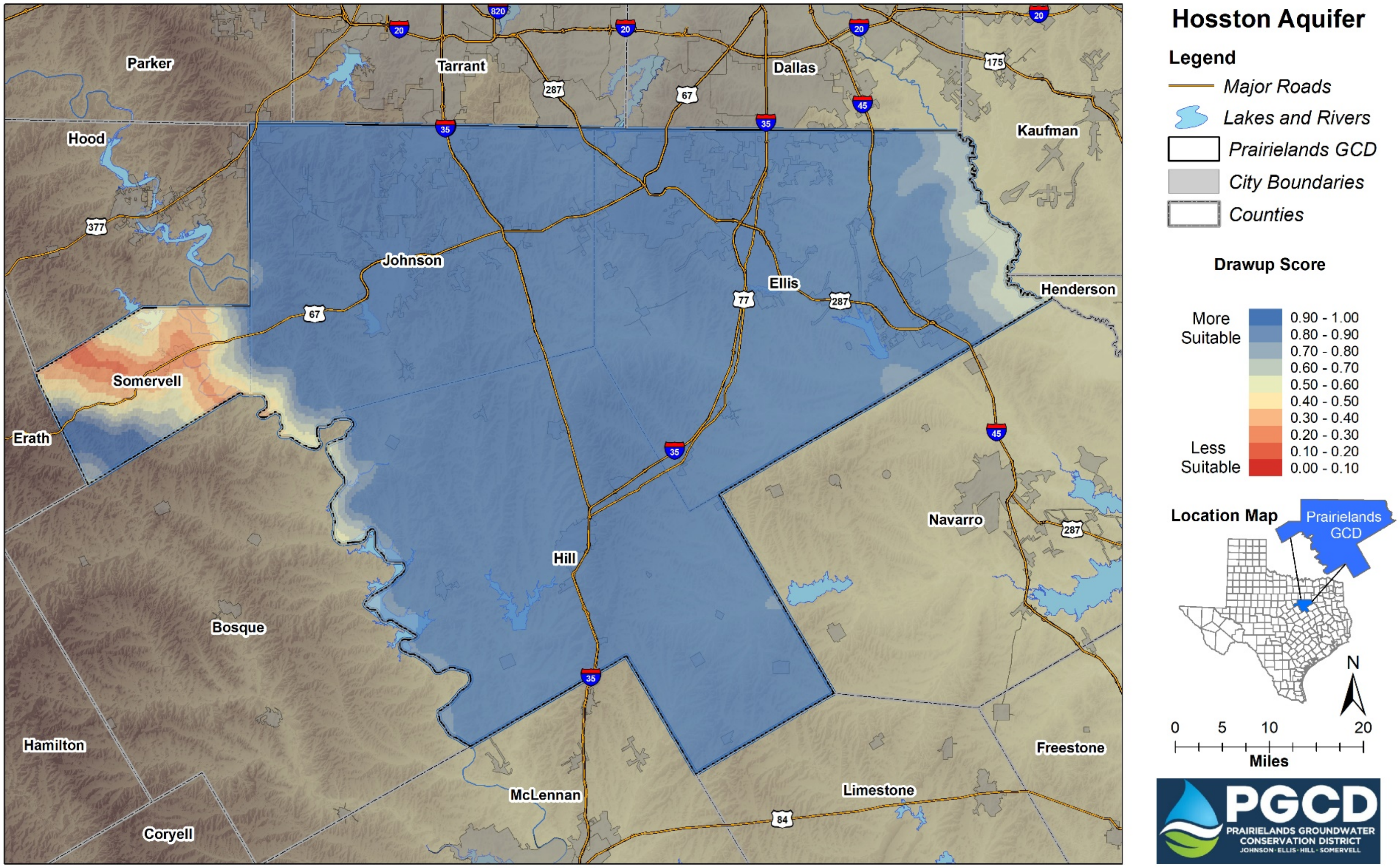
Miles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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Drawup Score
More Suitable
Less Suitable
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0.30 - 0.40
0.20 - 0.30
0.10 - 0.20
0.00 - 0.10
Location Map
Prairielands GCD
N
0 5 10 20
Miles
Parker
Tarrant
Dallas
Kaufman
Hood
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Somervell
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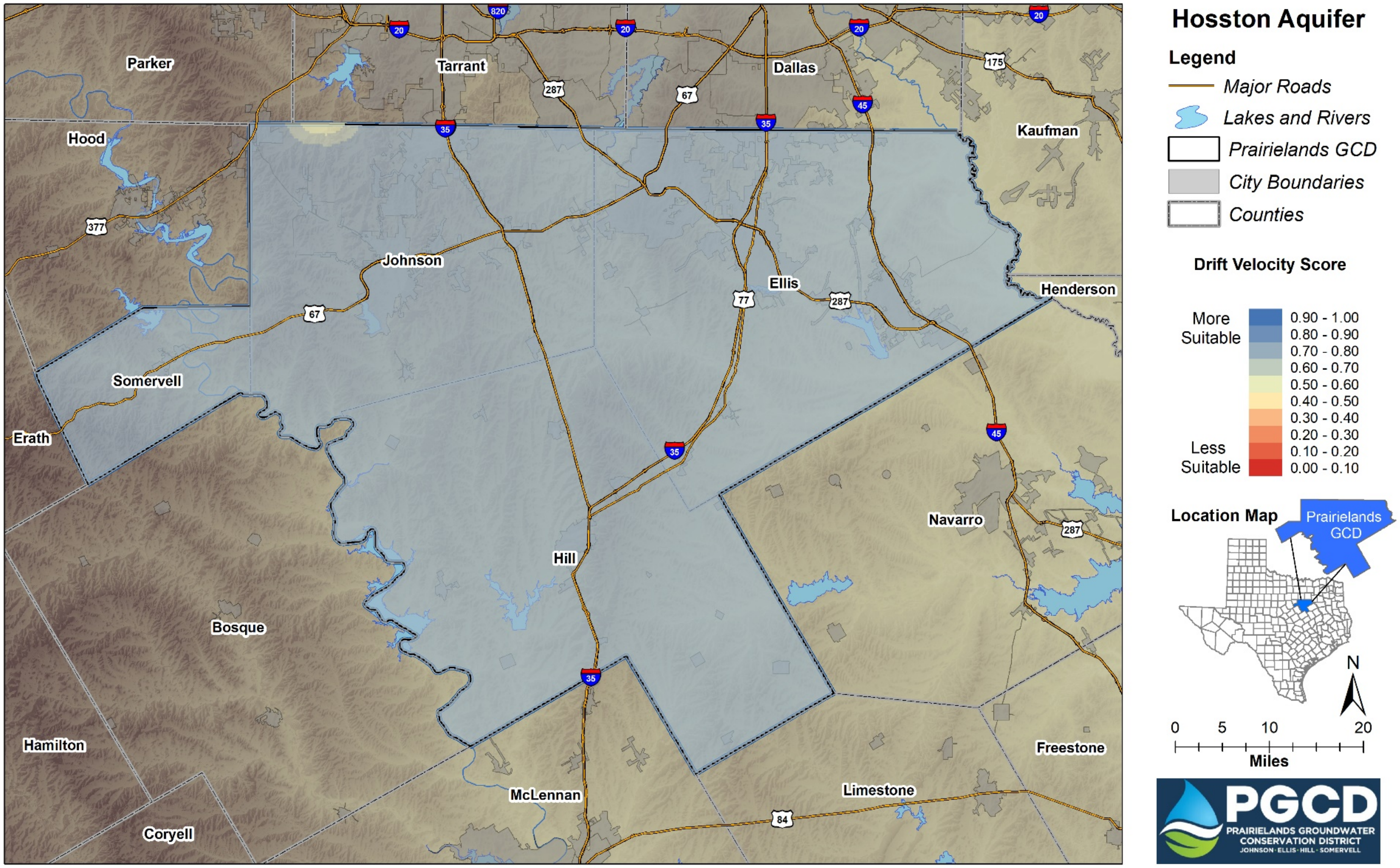
McLennan
Limestone
Freestone
Coryell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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Drift Velocity Score
More Suitable
Less Suitable
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Location Map
Prairielands GCD
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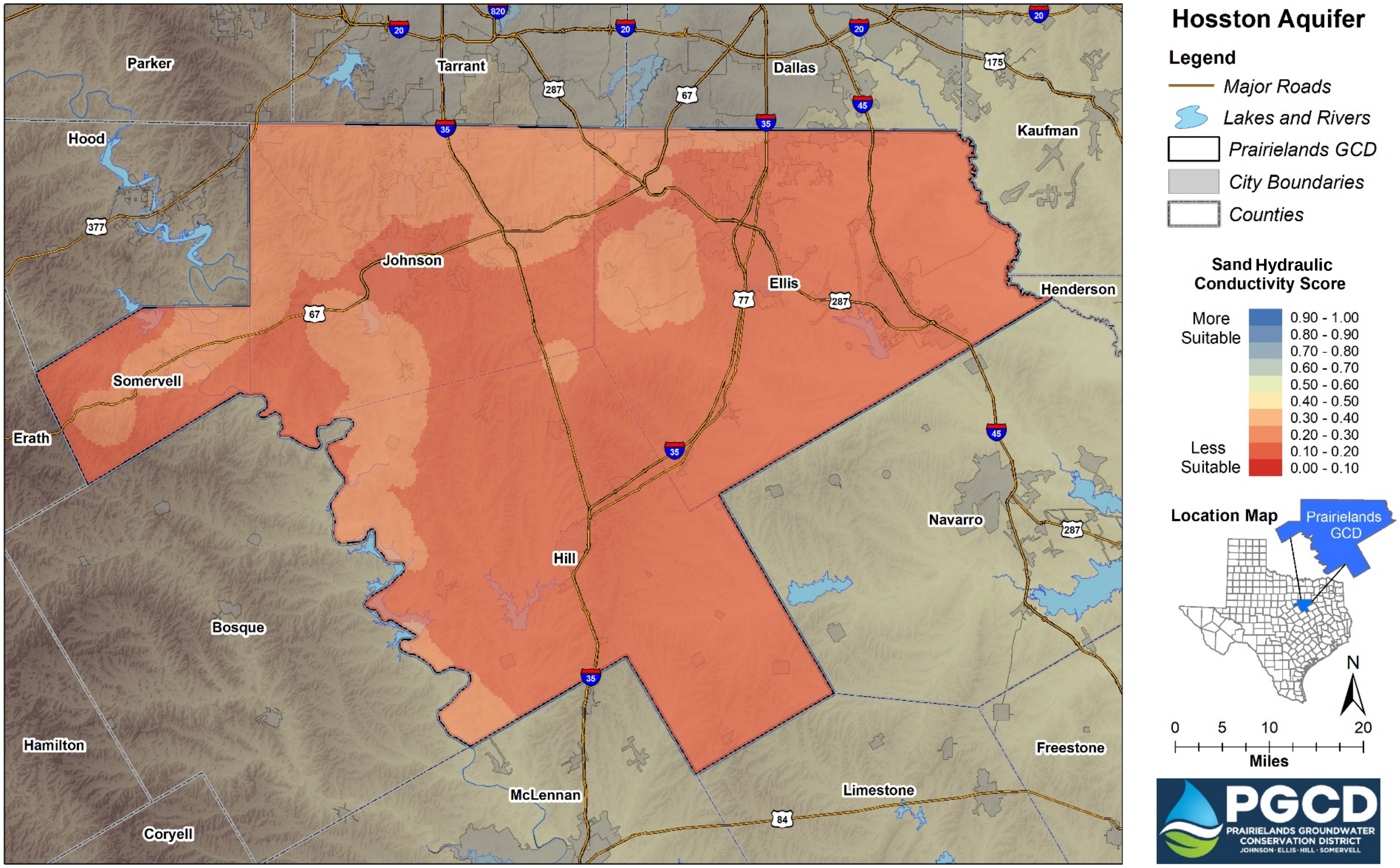
Limestone
Freestone
Coryell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Limestone
Freestone
Coryell
Hosston Aquifer
Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Sand Hydraulic Conductivity Score
More Suitable
Less Suitable
0.90 - 1.00
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Location Map
Prairielands GCD
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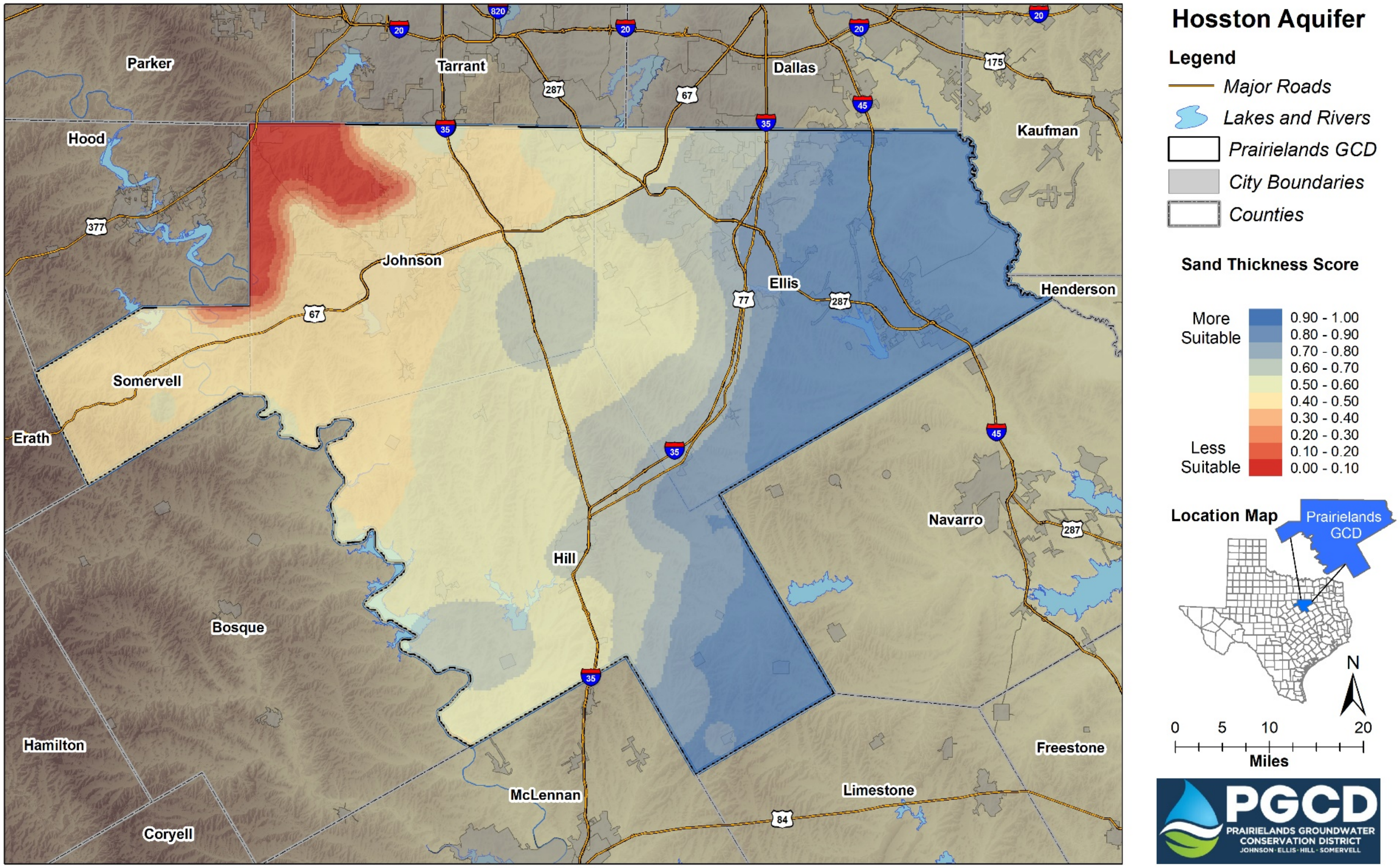
Miles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Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Sand Thickness Score
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Less Suitable
Location Map
Prairielands GCD
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Miles
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Somervell
Erath
Navarro
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Bosque
Hamilton
McLennan
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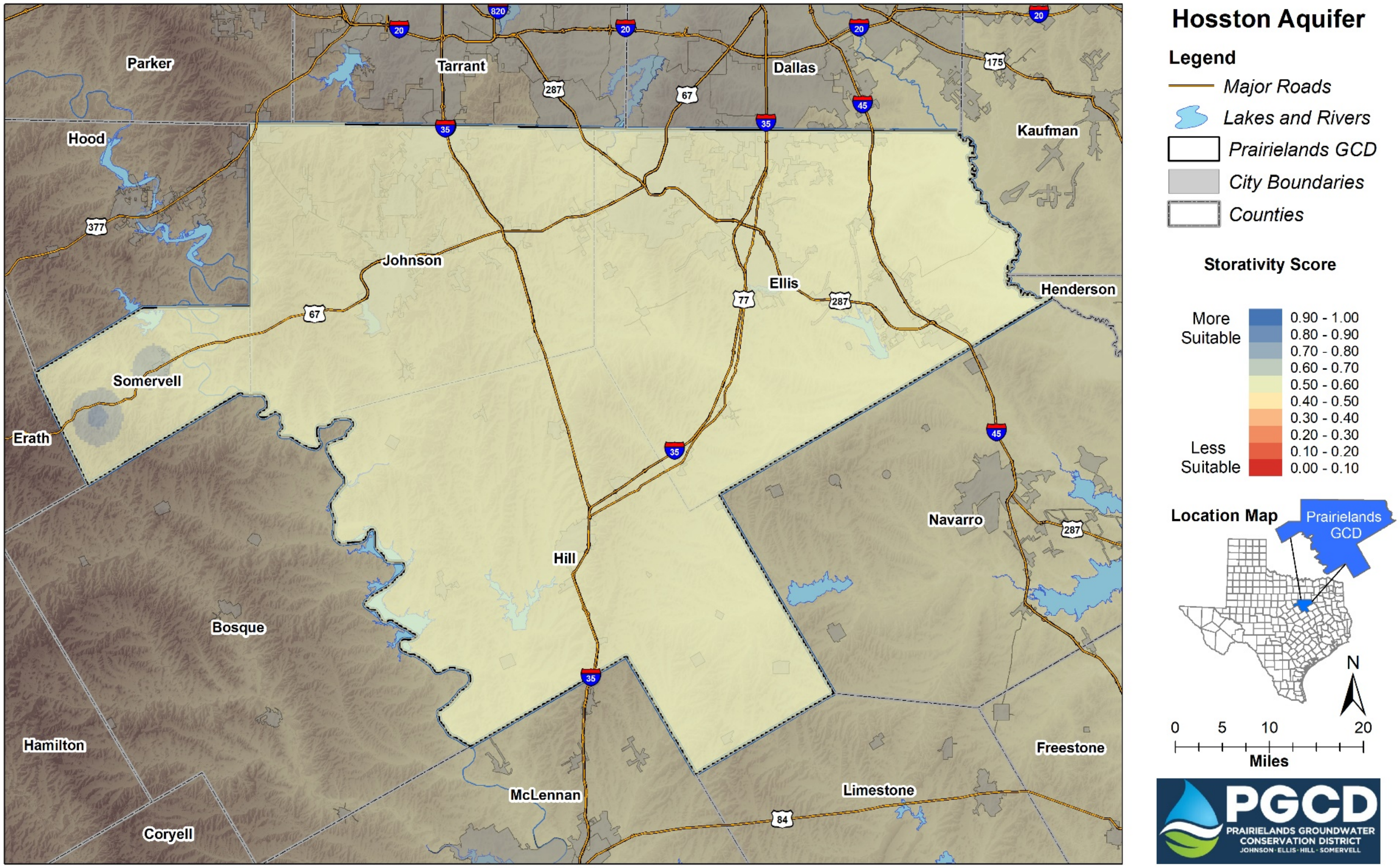
PGCD
PRAIRIELANDS GROUNDWATER CONSERVATION DISTRICT
JOHNSON · ELLIS · HILL · SOMERVELL


Hosston Aquifer
Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Storativity Score
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Less Suitable
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Location Map
Prairielands GCD
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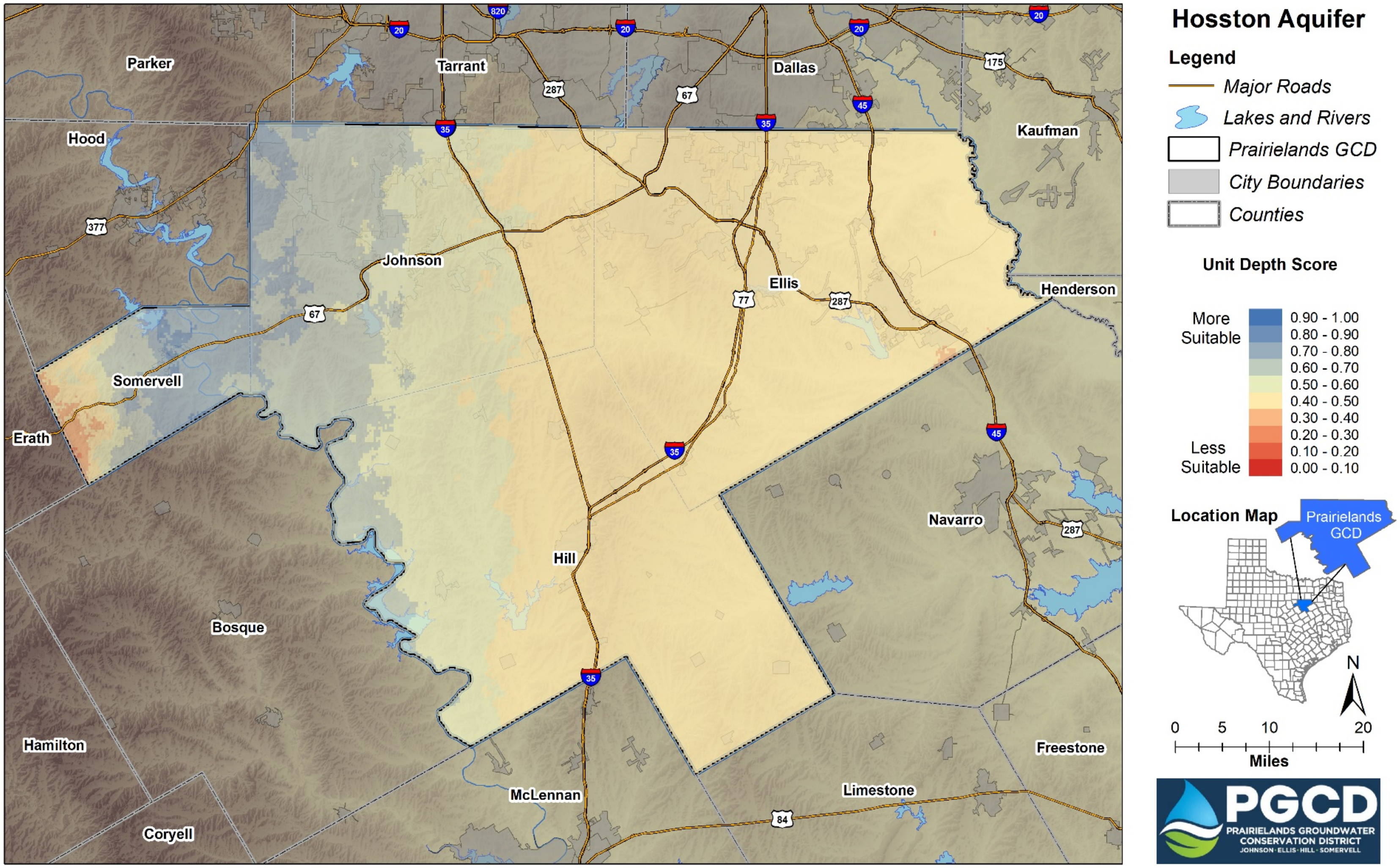
Coryell


Hosston Aquifer
Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Unit Depth Score
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Less Suitable
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0.00 - 0.10
Location Map
Prairielands GCD
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0 5 10 20
Miles
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Tarrant
Dallas
Kaufman
Hood
Johnson
Ellis
Henderson
Somervell
Erath
Navarro
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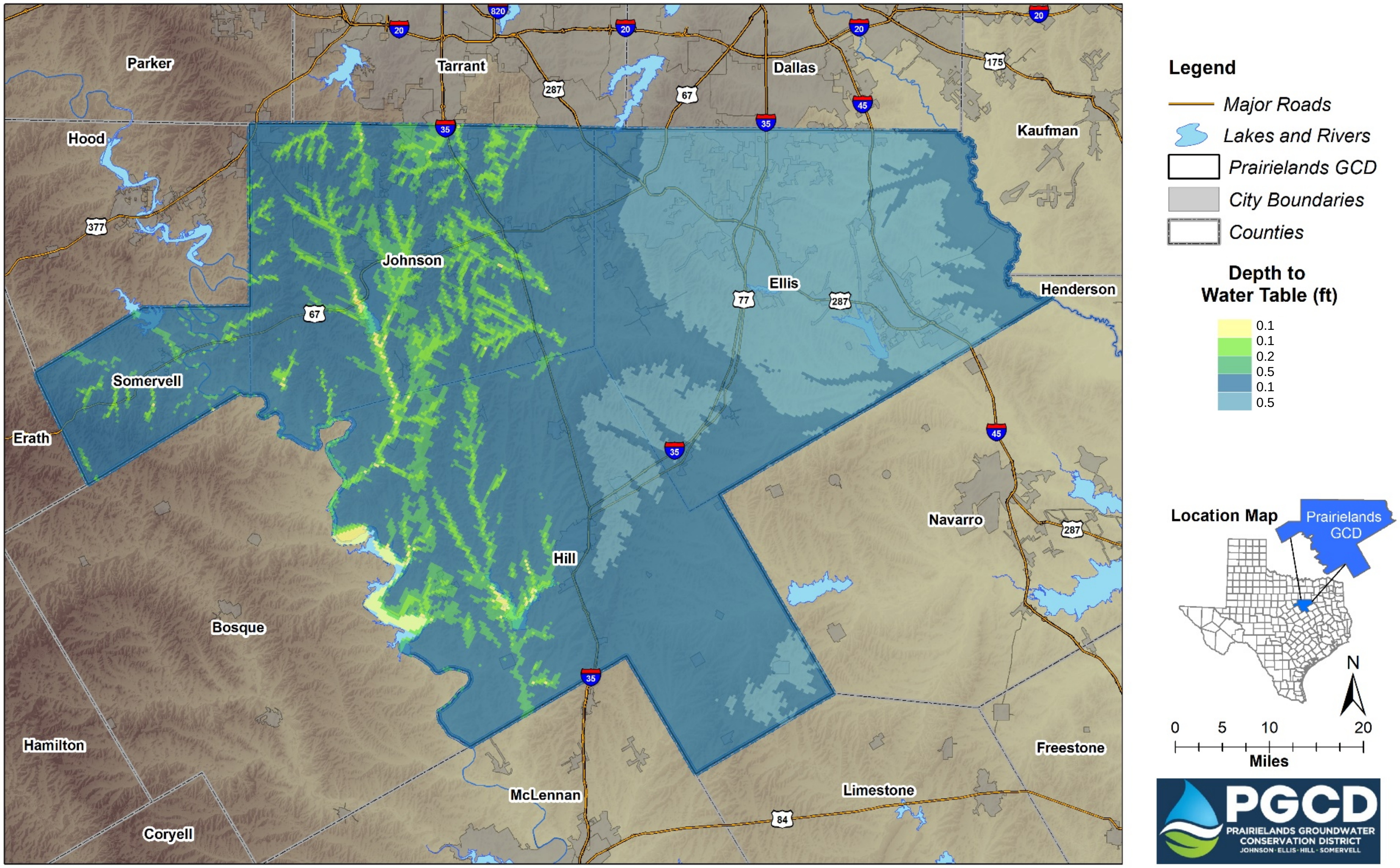
McLennan
Limestone
Freestone
Coryell

APPENDIX F:
AQUIFER RECHARGE - HYDROGEOLOGIC PARAMETER SCORES


Parker
Tarrant
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Hood
Kaufman
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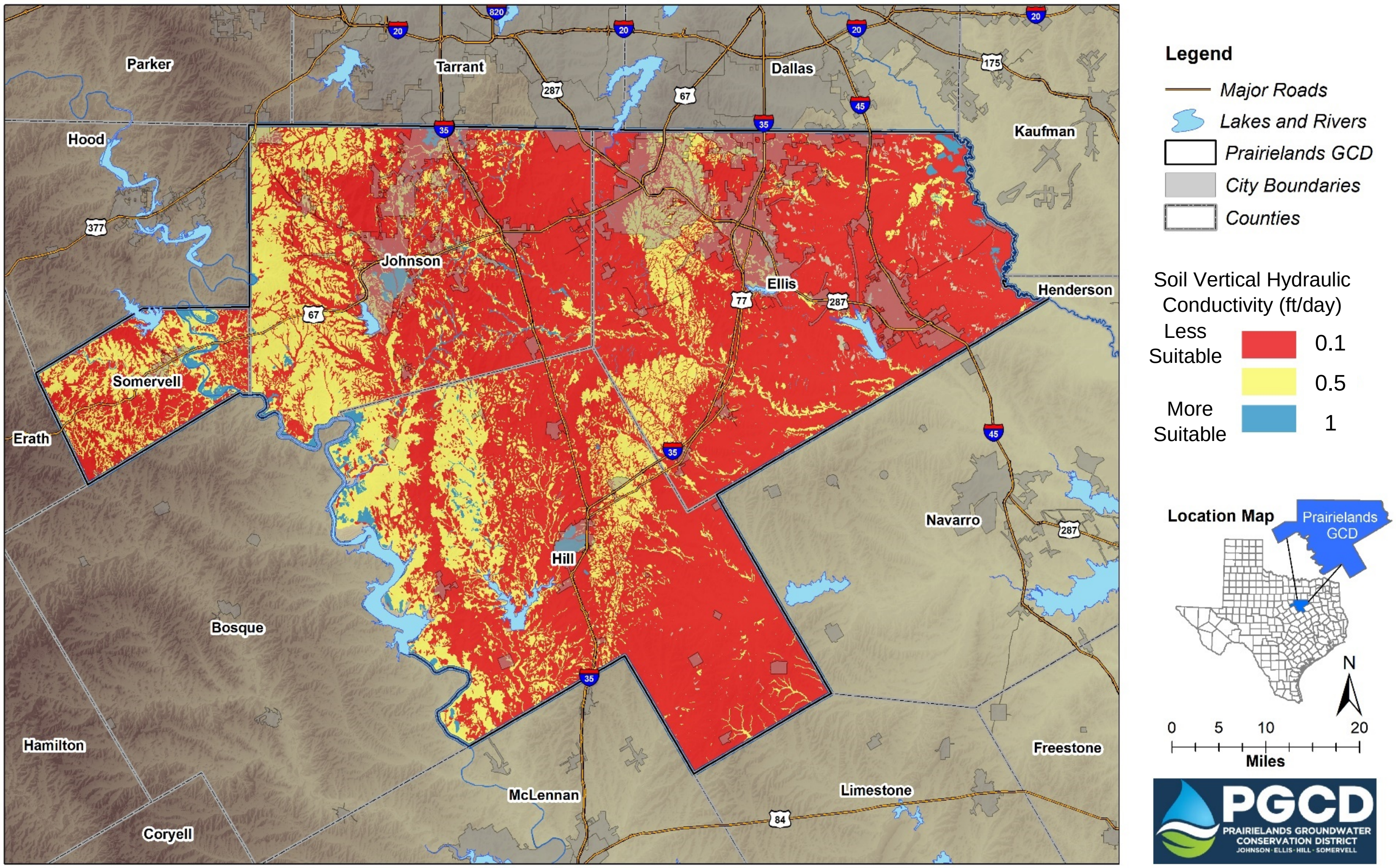
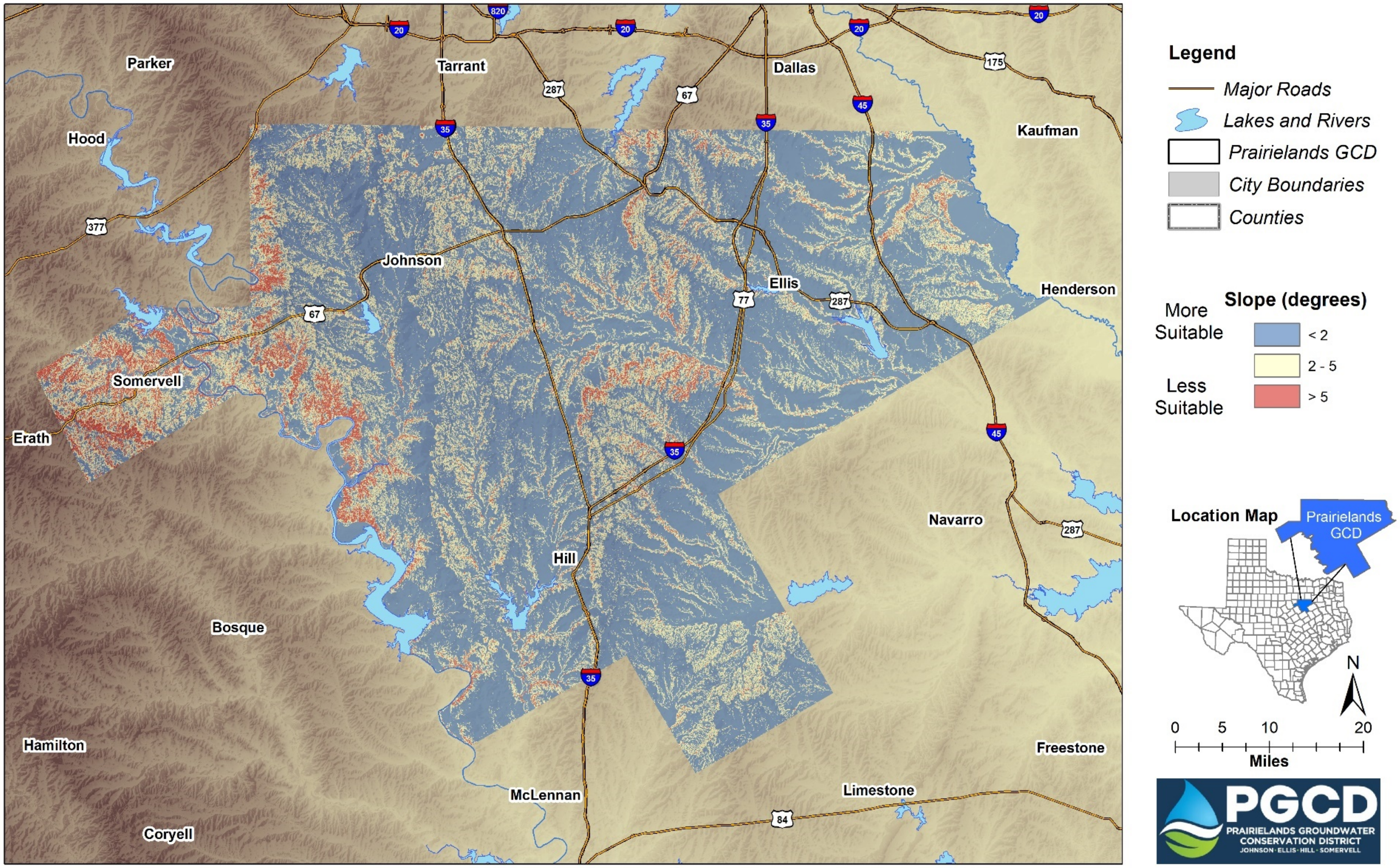
Hill
Bosque
Hamilton
McLennan
Limestone
Freestone
Coryell
Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Depth to
Water Table (ft)
0.1
0.1
0.2
0.5
0.1
0.5
Location Map
Prairielands
GCD
N
0 5 10 20
Miles


Parker
Tarrant
Dallas
Kaufman
Hood
Johnson
Ellis
Henderson
Somervell
Erath
Navarro
Hill
Bosque
Hamilton
McLennan
Limestone
Freestone
Coryell
Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Soil Vertical Hydraulic Conductivity (ft/day)
Less Suitable
0.1
0.5
More Suitable
1
Location Map
Prairielands GCD
N
0 5 10 20
Miles


Parker
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Somervell
Erath
Navarro
Hill
Bosque
Hamilton
McLennan
Limestone
Freestone
Coryell
Legend
Major Roads
Lakes and Rivers
Prairielands GCD
City Boundaries
Counties
Slope (degrees)
More Suitable
Less Suitable
< 2
2 - 5
> 5
Location Map
Prairielands GCD
N
0 5 10 20
Miles