2022 Recommended Land Management for the Water Quality Protection Lands Austin, Texas

Submitted by the
Department of Ecology & Conservation Biology
Texas A&M University

to the
Water Quality Protection Lands
Wildland Conservation Division
Austin Water

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Executive Summary

Background

This land management plan for the City of Austin's Water Quality Protection Lands (WQPL) focuses on the continued supply of high-quality water to Barton Springs in Zilker Park, Austin. These springs are discharge features of the Barton Springs segment of the Edwards Aquifer located in Hays and Travis counties south of the Colorado River. In addition to the high recreation value of the pool fed by these springs, Barton Springs is also home to the Barton Springs salamander (*Eurycea sosorum*), which was listed as endangered on April 30, 1997, and the Austin Blind salamander (*Eurycea waterlooensis*), which was listed as endangered on September 19, 2013. Moreover, the Barton Springs segment of the Edwards Aquifer is also the primary source of drinking water for thousands of people and, if Austin Water pursues indirect potable reuse through Lady Bird Lake and capture local inflows to Lady Bird Lake (one of the most economical options for meeting future water demands in the City's Water Forward Integrated Water Resource Plan), then the Barton Springs segment of the aquifer will become even more important.

To address conservation concerns over the effects of development on water that feeds Barton Springs, the City of Austin purchased 12,041.7 acres in fee title land (Figure I) and 22,132.4 acres of conservation easements between 1998 and 2022 using $238.4 million generated by voter approved bonds. The fee title properties occur in six watersheds: Bull Creek, Barton Creek, Slaughter Creek, Bear Creek, Little Bear Creek, and Onion Creek, and they are managed under the stewardship of Austin Water.

In 2001, the Land Management Planning Group developed a land management plan for the fee title properties and in 2012 the Lady Bird Johnson Wildflower Center updated the land management plan, accounting for new properties and land management research. In 2021, the City signed an interlocal agreement with the Department of Ecology & Conservation Biology at Texas A&M University to fully revise and update the management plan for the WQPL fee title properties for the next decade. This document represents the latest updated land management plan for the WQPL for that period 2022-2032.

The Issue and Goals

Barton Springs is fed by subterranean water that discharges from the Edwards Aquifer. This karst aquifer is characterized by soluble carbonate bedrock that facilitates rapid groundwater recharge, preferential flow pathways, and shallow soils. Fractures along and adjacent to numerous faults along the eastern edge of the Edwards Plateau tend to increase recharge and, because there is minimal filtration of water entering the aquifer, this leads to sensitivity of water quality in the area. The discharge from the Barton Springs Segment of the Edwards Aquifer is at least 44 million m^3/year and there are also substantial withdrawals from this aquifer. Major stream channels contribute about two thirds of total groundwater recharge and diffuse upland recharge contributes the remaining one third.

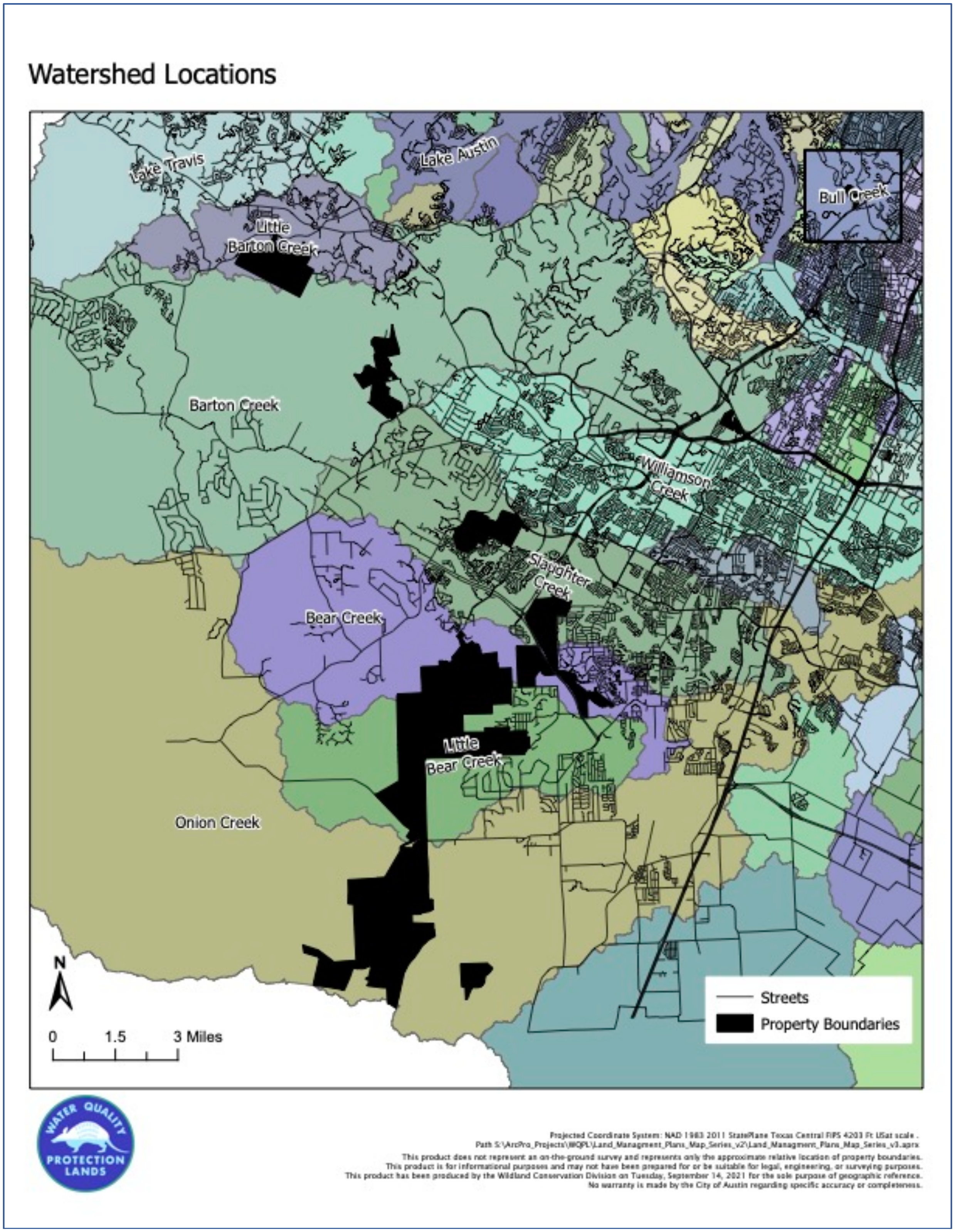

Figure I. Location of City of Austin Water Quality Protection Lands within the watersheds that provide recharge water for the Barton Springs segment of the Edwards Aquifer.

Maintenance of high-quality water in Barton Springs segment of the Edwards Aquifer is critical to protect the endangered salamander species and to feed the Barton Springs pool with clean water and for current and future potable water supply.

To achieve the goal of directing land management planning and implementation to protect water quality and quantity, several management priority areas have been identified. These include:

- Manage vegetation to maintain or improve infiltration of high-quality water.
- Balance land use and management options with water quality/quantity protection.
- Reduce contamination of runoff water due to on- and off-site activities.
- Protect or enhance riparian areas and riparian buffer strips to enhance water quality.
- Protect and enhance biodiversity for the benefit of habitat and watershed function.
- Work with City officials and stakeholders to acquire adequate budgets for project success.

Additionally, issues should be addressed in the broader context of sound natural resource management to maintain critical ecosystem services in the face of anthropogenic and climate-related threats to biodiversity. Aside from surface water filtration and infiltration, ecosystem services derived from the WQPL include wildlife habitat provision, pollination, and native biodiversity maintenance. It is also important to address issues that do not directly affect water provisioning or other ecosystem services but are critical to project success. This includes the maintenance of an appropriate public participation process that emphasizes equity among all social groups, addresses public access issues, and helps to build relationships between stakeholders and the City. Finally, issues that are not critical to the success of the project but that will enhance the overall quality of the project should also be addressed. These include seeking funding to support future acquisition of land, supporting natural resource-related education, maintaining the rural character of these lands, preserving cultural and historic resources associated with them, and assisting with research to improve watershed and ecosystem management for central Texas.

Management Recommendations

The land management plans developed in 2001 and 2012 provided management recommendations based on 1-8 treatment units for each of the nine management units (fee simple properties). The management recommendations were based on past land use, ecological sites, and physical features, and each was assigned an overall vegetative goal and treatment regime. While these were spatially explicit land management recommendations, there was a tremendous amount of duplication of recommendations that did not facilitate application of appropriate land management in a straightforward manner. To address this limitation of the previous land management plans, this update of the WQPL Land Management Plan focuses on four broad land cover categories that occur to various extents across all 11 current management units that constitute the WQPL fee title properties. The four land cover categories as well as key management recommendations for each are summarized below.

Savanna Grassland – areas that are >3,000 acres, mostly contiguous tracts of land dominated by herbaceous cover. The scale and grass dominance of these areas is conducive to land management interventions that limit woody plant canopy cover below climatic maxima to benefit the goals of water provisioning and biodiversity maintenance.

In these areas, vegetation management should maintain woody cover as far below 30% as practical. They should be exposed to moderate intensity surface fires at 2–4 year intervals, with higher and lower frequencies where canopy cover approaches 30% and 10%, respectively. Mechanical thinning may be beneficial where canopy cover exceeds 30% or where target fire frequency and intensity cannot be achieved. Broadcast herbicide treatments are generally not recommended, but herbicides can be used as targeted individual plant treatments to manage invasive species. Mowing and haying as well as targeted grazing are not recommended because of large area size and the cost of fencing and staff required to apply. Grazing with livestock is not recommended because of potential flushing of fecal matter into recharge features, and more soil erosion in sensitive riparian areas. Conversely, targeted browsing is recommended where moderately palatable woody plants that limit fine fuel continuity may be otherwise difficult to manage; however, this option may be impractical due to the challenge of containing goats. Seeding treatments can reduce soil erosion and improve plant diversity and ground cover in exposed areas where the seed bank is inadequate. Seed application to bare or distributed areas following fire or mechanical treatments is important but ensuring good soil contact may incur significant labor cost and it may be necessary to apply seed multiple times due to weather variability.

Savanna Woodland – woodlands that do not support Golden cheeked warblers, generally have patchy or low herbaceous cover, and are dominated by trees with >8” diameter at breast height. These areas are generally not receptive to grassland restoration but may benefit from limited or patch-scale canopy reduction such as from prescribed burns.

These areas are generally not conducive to the same management approach as savanna grasslands because of abundant mature trees and poor or discontinuous herbaceous cover. Where possible, it is recommended that these areas are periodically exposed to fire under safe burning conditions to limit encroachment into adjacent grasslands and to improve oak recruitment and understory plant diversity. Occasional mechanical thinning and targeted browsing by goats to enable light penetration may improve surface fuel loads, plant diversity, oak recruitment, and resilience to climate-related stressors. These areas are not suited to mowing, haying, or grazing, and herbicide applications are recommended only where introduced species with high invasion potential occur at low levels.

Interface Savanna – areas that are <1000 acres tracts of land that are adjacent to or embedded within developed areas and that are dominated by herbaceous cover but may also have significant woodland. Their smaller size and proximity to development constrain land management options, can increase the cost, complexity, and risk associated with each land treatment, and can limit the benefit to natural resource objectives such as water provisioning and biodiversity.

In these areas, fire return intervals of 4 years or less may be optimal to maintain woody canopy cover, but longer intervals may be preferable due to proximity to developments. Mechanical and herbivory treatments may ensure that a 10-year fire return interval is sustainable, and smaller woody plants could be manually removed by volunteers annually. Herbicides are recommended where introduced species with high invasion potential occur at low levels. Mowing, haying, grazing, and browsing may be useful to reduce accumulated fine fuel loads, especially along property boundaries. Importantly, interface savannas can provide excellent opportunities for community engagement and support from partnering agencies, such as Austin Fire Department.

Warbler Woodland – areas that are occupied nesting habitat for the endangered Golden-cheeked warbler. Management of these areas must follow the Texas Parks and Wildlife document entitled, "Management Guidelines for the Golden-cheeked Warbler in Rural Landscapes".

Canopy reducing treatments are legally not permissible in these areas, except for maintaining fence lines and trails. Mechanical thinning followed by prescribed fire and targeted browsing treatments could improve the resilience of these woodlands; however, a special permit from the US Fish and Wildlife Service would be required. Such treatments are consistent with the WQPL mission because drought- or wildfire-related collapse of mature woodlands would compromise the quality of water entering the aquifer. Mechanical or herbicide treatments of non-native invasive species are strongly recommended in warbler woodlands. While deer culling is currently not planned for the WQPL, if it is used in the future, occupied Golden-cheeked warbler habitat should be included.

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1 Background and Natural Resources Information

1.1 Historical Overview

This land management plan for the City of Austin's Water Quality Protection Lands (WQPL) focuses on the continued supply of high-quality water to Barton Springs in Austin. This natural wonder is often called the Crown Jewel of Austin because of its exceptionally clear water. It consists of four natural springs located at Barton Creek in Zilker Park. These springs are discharge features of the Barton Springs segment of the Edwards Aquifer located in Hays and Travis County south of the Colorado River. In addition to the high recreation value of the pool fed by these springs, Barton Springs is also home to the Barton Springs salamander (*Eurycea sosorum*), which was listed as endangered on April 30, 1997, and the Austin Blind Salamander (*Eurycea waterlooensis*), which was listed as endangered on September 19, 2013. Moreover, the Barton Springs segment of the Edwards Aquifer is also the primary source of drinking water for thousands of people and, if Austin Water pursues indirect potable reuse through Lady Bird Lake (one of the most economical options for meeting future water demands in the City's Water Forward Integrated Water Resource Plan) then the Barton Springs segment of the aquifer will become even more important.

From 1974-1980, burgeoning highway construction and unregulated development in the Barton Creek watershed and the Edwards Aquifer recharge zone began threatening the quality of the subterranean water that feeds Barton Springs. Growing public concern over this threat resulted in three environmental groups and the conservation district suing the Texas Department of Transportation in 1989 to stop construction of the southern extension of Texas State Highway Loop 1 (also known as the MoPac Expressway). The following year public action resulted in the City Council rejecting the Barton Creek Planned Unit Development and strengthening of the 1986 Comprehensive Watersheds Ordinance, under the acronym SOS: "Save Our Springs." In 1993 the Legislature enacted Senate Bill 1029 to grandfather developments with permits filed prior to subsequent municipal water quality regulations, but the reigning governor vetoed the bill. However, the next governor approved new laws in 1995 limiting Austin's regulatory powers over development.

This legislative seesaw led City of Austin voters to approve two separate utility bonds (Proposition 2 in May and Proposition 8 in November 1998) to protect the quality of water feeding Barton Springs. Subsequently, additional voter-approved utility bonds were passed in 2000, 2006, 2012, and 2018 raising a total of $238.4 million. These bonds made funds available to purchase fee title or easements on lands deemed critical for watershed protection in southwestern Travis and adjacent northern Hays counties, Texas.

As of September 2022, Austin Water has purchased 12,041.7 acres in fee title land and 22,132.4 acres of conservation easements using these funds. All properties lie within either the contributing or recharge zone of the Barton Springs segment of the Edwards Aquifer that discharges, in part, into the Barton Springs swimming pool (see Figure 1). These properties are in six watersheds: Bull Creek, Barton Creek, Slaughter Creek, Bear Creek, Little Bear Creek, and Onion Creek. Attempts were made to purchase fee title properties adjoining one another to create contiguous habitat, preserve greater ecological function for water quality protection, and facilitate effective land management.

Historically, most of the sites were used for livestock and/or exotic game production, and many show evidence of poor grazing management and fire exclusion. This mismanagement led to woody plant encroachment, loss of perennial native grasses, and erosion problems.

The fee title properties are managed under the stewardship of Austin Water. In September 1999, the City of Austin hired the Land Management Planning Group (LMPG) to develop a land management plan for the fee title properties, which have been since termed the WQPL. The LMPG was a consortium of for-profit environmental consulting firms and non-profit organizations assembled to conduct a wide range of natural resource inventories, oversee an involved public stakeholder process, develop a GIS database, and recommend site-specific land management. The consortium was led by the Lady Bird Johnson Wildflower Center and included Loomis Austin, Inc., The Nature Conservancy of Texas, and American YouthWorks. Work for this project was also conducted by the U.S.D.A. Natural Resource Conservation Service, Glenrose Engineering, Inc., Paul Price and Associates, and Selah, Bamberger Ranch Preserve. In 2008, the City hired the Lady Bird Johnson Wildflower Center to update the original land management plan, accounting for new properties purchased and new land management research. In 2021, the City signed an interlocal agreement with Texas A&M University for key faculty in the Department of Ecology & Conservation Biology to fully revise and update the management plan for the WQPL fee title properties for the next decade. This document represents the latest updated land management plan for the WQPL for the period 2022-2032.

1.2 Geology of Karst Ecosystems

Karst terrain are landscapes underlain by soluble carbonate bedrock and include caves, sinking streams, aquifers, and springs. Karst systems support rapid groundwater recharge, preferential flow pathways, shallow soils, and clay soils that crack with desiccation (Ford and Williams 2007).

No geological analysis has been conducted as a portion of this contract, though a significant amount of geological analysis has been done on the region underlying the recharge zone that feeds the Barton Springs Segment of the Edwards Aquifer. Information presented here, unless otherwise noted, comes from the Barton Springs/Edwards Aquifer Conservation District or the Texas Cave Management Association. The geologic units that comprise the Recharge Zone are the seven members of the Edwards Limestone and the Georgetown Formation. The Marine member is present only in the southern portion of the Recharge Zone. The Leached/Collapsed member outcrops cover large areas along the eastern edge of the Recharge Zone and contains many caves. The Regional Dense member acts as a confining unit and concentrates water flow, which promotes cavern development. The Grainstone member is a relatively large unit that protects the numerous caves that occur in the underlying Kirschberg member. The Dolomitic member is not as prolific a cave-forming member but contains larger sized passages due to the nature of the bedrock. The Walnut member is a very marly limestone (i.e., limestone with a large clay content). This member is not a good cave-forming layer. Beneath the Edwards is the Glen Rose limestone, a relatively impervious member that is hydrologically connected to the Edwards Aquifer. The fracturing along and adjacent to the numerous small faults along the eastern edge of the Recharge Zone tend to increase the amount of recharge and thus the sensitivity of this area (Russell and Jenkins 2001).

Approximately 50 million Americans, including more than half the population of Texas, rely on karst aquifer for water supply (Stevanovic 2019). At least 44 million m^3/year must enter the Barton Springs Segment of the Edwards Aquifer as recharge since this is the average discharge from the aquifer, and recharge and discharge must be in balance in a natural steady-state groundwater system (Veni 2000). This amount underestimates actual recharge, however, because it does not account for withdrawal from this aquifer (i.e., wells). Hauwert (2016) estimates that major stream channels contribute 56-67% of total groundwater recharge, while upland autogenic recharge and other smaller sources contribute 33-44%; as percentage of precipitation over the Edwards Aquifer outcrop source area, autogenic recharge from upland and riparian sources is 22-28%. These estimates are higher, more rigorous, and better calibrated than prior estimates. The protection and management of these vital water resources are critical to public health and to sustainable economic development. The United Nations has specifically identified groundwater as an essential resource for water security, socio-economic development, climate change resilience, and the fight against poverty (United Nations 2022). Management of karst features on the WQPL is described in Appendix 1.

1.3 Soils and Ecological Characteristics

The WQPL are composed of 24 distinct soil types (USDA NRCS 2013). Soil type is based on general slope of the area, composition of the parent material, and subsequent percentages of clay, silt, sand, and rock. Each of these soil types has been evaluated for a range of factors, including erosion potential (*K*). A table containing soil types in or around the WQPL, their associated ecological sites, and the K-factor value is given in Table 1 and the soil types within each watershed unit are mapped in Figures 2-12.

Soil types that historically supported similar vegetation communities are grouped into ecological sites. Each ecological site description includes mean annual biomass production, an assessment of its suitability for grazing, historical climax plant community, plant species that appear and disappear under heavy grazing, and huntable wildlife native to the area. A useful analysis of the current condition of a given piece of land can be obtained by comparing the current assemblage and biomass of species to the historical climax system described in the ecological site description. The ecological sites within each management unit are mapped in Figures 13-23.

Most ecological sites found within the WQPL historically supported savanna communities with less than 30% woody cover, with denser woody cover tending to occur in steeper draws that fire accessed less frequently (Smeins 1997; also see section 2.1 of this document). The historical plant communities associated with various ecological sites found within the WQPL are listed in Table 2.

Table 1: Soil types and erosion potential factors (K) on Water Quality Protection Lands.

Name	Ecological Site	K Factor
Anhalt clay	Deep Redland	0.32
Brackett soils	Adobe	0.37
Brackett soils, rock outcrop	Steep Adobe	0.37
Crawford clay	Deep Redland	0.32
Comfort rock outcrop	Low Stony Hills	0.10
Denton silty clay	Clay Loam	0.32
Eckrant rock outcrop	Steep Rocky	0.10
Ferris-Heiden complex	Eroded Blackland	0.32
Heiden clay	Blackland	0.32
Krum clay	Clay Loam	0.32
Lewisville silty clay	Clay Loam	0.32
Mixed alluvial land	Loamy Bottomland	0.15
Oakalla complex	Loamy Bottomland	0.32
Patrick soils	Chalky Ridge	0.32
Purves clay	Shallow	0.32
Rumple comfort complex	Gravely Redland	0.17/.10
San Saba clay	Redland	0.32
Speck clay loam	Redland	0.32
Speck stony clay loam	Redland	0.32
Tarpley clay	Redland	0.32
Tarrant soils	Low Stony Hills	0.32
Tarrant and Speck soils	Low Stony Hills	0.32
Tarrant soils and rock outcrop	Steep Rocky	0.32
Volente complex	Clay Loam	0.32

Table 2: Historical plant communities of the Water Quality Protection Lands.
(USDA NRCS 2013; Diamond 1997)

Ecological Site	Historical Plant Community	Historic Woody Canopy % Cover
Adobe	**Open grassland/Oak Hillside:** Fire maintained community of tall and midgrasses and scattered oaks.	10%
Blackland	**Tallgrass Prairie:** Fire maintained community dominated by warm-season, perennial tallgrasses with warm-season, perennial midgrasses filling most of the remaining species composition.	5%
Chalky Ridge	**Tallgrass Prairie:** Fire maintained community of tallgrasses with significant component of midgrasses, scattered trees and low growing shrubs.	less than 15%
Clay Loam	**Tallgrass Savanna:** Fire maintained tallgrass plant community interspersed with occasional perennial forbs and woody species.	less than 10%
Deep Redland	**Post Oak Savanna:** Fire maintained savanna composed of tallgrasses and scattered post oaks.	less than 10%
Eroded Blackland	**Tallgrass Prairie:** Fire maintained mosaic of tallgrass and midgrass plant communities. Midgrasses dominate shallower eroded areas.	less than 5%
Gravelly Redland	**Mixed Grass Prairie:** Fire maintained midgrass community with scattered tallgrasses, trees, and shrubs.	less than 10%
Loamy Bottomland	**Hardwood Grassland:** Fire maintained tallgrass community typical of first level bottomland near a river or perennial creek. Characterized by a mix of tallgrasses and hardwood, with high plant diversity.	20—50%
Low Stony Hills	**Open Grassland with Oak Mottes:** Fire maintained open grassland with scattered oak motts.	20%
Redland	**Oak Savanna:** Fire maintained savanna composed of tallgrasses and scattered post oaks.	less than 10%
Shallow	**Tall and Midgrass Prairie:** Fire maintained tall and midgrass community with widely scattered live oak trees and mottes.	less than 5%
Steep Adobe	**Texas Oak/Live Oak Savanna:** Plant communities of these steeper slopes (12-60% gradient) have a larger component of woody species (occurring in bands perpendicular to the slope) than the Adobe site.	20%
Steep Rocky	**Tall and Midgrass/Oak Hillside:** Mixture of many woody species along with tallgrasses, midgrasses and forbs. Fire was less frequent here than on adjacent flatter slopes. Density and frequency of woody vegetation dependent on presence or absence of fractured limestone and exposure. Where non-fractured geology exists, canopies will be less dense. North facing exposures have higher canopy cover and larger trees than southern exposures. Referred to as "cedar brakes" by early explorers.	35%
Slopes, Canyons, and Creek Sides (occasionally, Flat/Rolling Uplands)	**Mature Ashe Juniper Woodlands:** Evergreen woodlands of large-diameter *Juniperus ashii* typically occur on long-unburned dry exposures or slopes. The woodlands may also contain live oak, several deciduous tree species, and an understory of deciduous shrubs. Due to landscape position and paucity of herbaceous fuels, old-growth juniper woodlands burn very infrequently, with stand-replacing, crown fires.	80-100%

A sharp distinction in plant composition and hydrologic function correlates with underlying geology. Trinity-derived substrates occur on the contributing zone of the Barton Springs segment of the Edwards Aquifer. Sloped areas tend to be steeper, are underlain by thin, inceptisols of the Bracket series, tend to lack introduced species, and support mixed native grasses, including Seep Muhly (*Muhlenbergia reverchonii*) and Tall Grama (*Bouteloua pectinata*), and a high diversity of forbs, such as Blackfoot Daisy (*Melanpodium leucanthum*), Green Lily (*Schoenocaulon texanum*), Ladies Tresses (*Spiranthes* spp.), and Woolly Ironweed (*Vernonia lindhiemeri*). These sites are known as "Steep Adobe" (Adobe in Table 2). King Ranch Bluestem (*Bothriochloa ischameum var. songarica*) occur in open valleys that receive stormwater runoff on the Volente series mollisols of the Trinity formation. By contrast, Edwards-derived substrates are gently rolling hills underlain by mostly thin and clay-heavy grassland-associated mollisols, which appear to be susceptible to invasion by old world bluestems including King Ranch, Silky (*Dicanthium sericea*), and Kleberg (*Dichanthium annulatum*) bluestems. The native grass community is characterized by Texas Wintergrass (*Nasella leucotricha*), Texas Cupgrass (*Eriochloa sericea*), Canada Wildrye (*Elymus canadensis*), and Silver Bluestem (*Bothriochloa laguroides*) and forbs including Snoutbean (*Rhyncosia senna*) and Mealy Blue Sage (*Salvia farinaceae*). Both Edwards- and Trinity-derived substrates support matrix grasses including Indiangrass (*Sorghastrum nutans*), Little Bluestem (*Schizachyrium scoparia*), Meadow Dropseed (*Sporobolus compositus*), Purple Threeawn (*Aristida purpurea*) and Sideoats Grama (*Boteloua curtipendula*), among many others, and forbs such as Wedelia (*Wedelia texana*), Antelope Horns (*Asclepias asperula*), Queen's Delight (*Stillingia texana*), and Plateau Goldeneye (*Viguera dentata*).

The eastern Edwards Plateau historically supported a mosaic of open grasslands, savannas with dispersed trees, and closed-canopy woodlands. However, this region was degraded by timber harvesting, fire suppression, invasive species introduction, overgrazing, and predator eradication. The leading drivers of degradation include suburban development, aggregate mining, excessive groundwater extraction, and climate change.

1.4 Species of Concern

Literature reviews and surveys are utilized to identify tracts containing plant or animal species that could affect land management. These species of concern include native species listed as threatened or endangered, native species that are regionally uncommon, and native or non-native undesirable species that cause ecological problems.

1.4.1 Faunal Species

1.4.1.1 Karst Invertebrates

Travis County caves contain six endangered karst invertebrates including: Tooth Cave pseudoscorpion (*Tartarocreagris texana)*, Tooth Cave spider (*Neoleptoneta myopica*), Tooth Cave ground beetle (*Rhadine persephone*), Kretschmarr Cave mold beetle (*Texamaurops reddelli*), Bone Cave harvestman (*Texella reyesi*), and Bee Creek Cave harvestman (*Texella redelli*). Additionally, there are 25 karst other species of concern in Travis County (Veni 2000).

These endangered species are troglobites, species that never leave the karst environment. Although all nutrients of the cave ecosystem flow in from the surface, the distribution of invertebrates extends far down into karst features. They feed on other insects or organic matter washed into the caves during rain events or carried in by fauna such as cave crickets. These species require the high humidity and constant temperatures found in caves (Campbell 1995). Changes to the humidity, structure, or nutrient flow into caves threaten these invertebrates (Culver 1982). Filling or covering caves with impervious materials has destroyed 20% of Travis County's known caves (Farmer 1999). Land management activities in a cave's drainage area that alter the surface flow into karst features or the nutrient level (e.g., removing native vegetation or adding synthetic fertilizers) can be equally damaging and should be avoided (Veni 2000). The important red fire ant (*Solenopsis invicta*) is also a serious threat to these species because they forage deep into caves, eating invertebrates and eggs and several endangered species (Wojcik et al. 2001). Cave crickets forage outside of caves at night and bring organic matter into karst features; therefore, disruption of their lifecycle by fire ants can impact entire cave systems (Campbell 1995).

1.4.1.2 Fisheries

No threatened or endangered fish are known or suspected to occur in any of the waters occurring on the WQPL. All surface waters of the WQPL are ephemeral.

1.4.1.3 Salamanders

Information in this section was provided by Nathan Bendik, City of Austin. Like many central Texas *Eurycea* salamanders, Barton Springs salamanders are typically less than three inches long, neotenic, and inhabit a narrow range within a karst aquifer system (Chippindale et al. 1993, Devitt and Nissen 2018). Their range overlaps with the Austin Blind salamander, which is currently only known from Barton Springs and is likely a deep aquifer specialist (Hillis et al. 2001). Barton Springs salamanders inhabit springs and groundwater habitats within the Barton Springs segment of the Edwards Aquifer and its contributing zone, which includes portions of the Trinity Aquifer (Devitt and Nissen 2018). The known range of this species has expanded dramatically since its original description (Chippindale et al. 1993); they have now been documented from wells within the aquifer, underground stream passages, and springs along Barton, Onion, and Little Bear creeks and the Colorado River (Bendik et al. 2013, McDermid et al. 2015, Devitt and Nissen 2018).

Most ecological research on Barton Spring salamander populations has occurred at Barton Springs, a large, modified ecosystem with four primary spring outlets. Studies spanning more than 20 years found that surface abundance of salamanders can vary greatly within a site over periods of more than a year, sometimes by orders of magnitude (Bendik and Dries 2018, Dries and Colucci 2018). This is likely due to real changes in population size and observation error when individuals move between surface and subsurface environments (Bendik et al. 2021). Typically, up to hundreds of individuals are observed during these surveys at Barton Springs. At smaller upland springs, encountering even one individual is uncommon because such springs tend to dry out and salamanders migrate underground or die from desiccation. Even when flowing, springs do not support large surface populations of salamanders, which are typically only observed within the vicinity of the spring orifices. Other central Texas *Eurycea* salamanders, e.g., San Marcos and Jollyville Plateau species, inhabit large groundwater-fed areas downstream of springs, including headwater rivers and streams (Tupa and Davis 1976, Bendik et al. 2016); however, Barton Springs salamanders have been documented only within tens of meters from spring orifices. This may be the result of different habitat preferences or tolerances for Barton Springs salamanders, a function of habitat features downstream of springs (e.g., anthropogenic factors, sinking vs. gaining streams), or a sampling artifact (inaccessible areas, infrequent searches). However, it is possible that salamanders could be encountered in new WQPL locations where groundwater is present, e.g., within the Bear Creek channel or within springs and seeps. Many visits may be required over the course of varying hydrologic conditions to document the species before concluding salamanders are absent from a site within their range.

Because Barton Springs salamanders occupy both springs and the aquifers that feed them, protection of water quality and quantity, and habitat structure are important components of conservation. WQPL manages for best water quality and water quantity practices and recommendations here emphasize physical habitat at spring outlet improvement. Barton Springs salamanders are more abundant when sedimentation within their surface habitat is low (Bendik and Dries 2018). They crawl into the spaces between rocks, and these areas become unavailable when sediments fill the crevices. Therefore, habitat management should seek to avoid embeddedness of cobble and gravel sized rocks with fine sediments. Erosion of fine sediments caused by historical land clearing and grazing, impervious cover, and feral hogs should be mitigated to the best extent practicable. This can include increasing natural vegetation cover near springs where grazing was the predominant land-use practice, creating fences around springs and spring runs to exclude feral hogs, and removing impervious cover within the spring-shed. Feral hog management should seek to reduce or eliminate their presence from WQPL tracts containing salamander habitat. If grazing is permitted, cattle should be fenced off from entering near creeks and springs to keep physical disturbance to the soil, surrounding vegetation, and habitat to a minimum. Minimizing human visitation would also be preferrable because people tend to directly modify spring habitats when they encounter them (e.g., Upper Barton Spring; Stillhouse Hollow Spring). For example, they remove cover for salamanders and will trample them. People also tend to ignore posted signage, so keeping public trails far away from any spring sites on WQPL land is recommended. Other impacts such as from heavy equipment, pesticides and direct impacts from fire should likewise be avoided in the spring flow area.

Improvement of spring run habitat may be attempted by:

- Restoring cover for salamanders in the form of cobble and gravel.
- Removing impoundments on spring runs.
- Flushing following restoration to remove accumulated sediments from interstitial spaces to ensure salamander abundance during quarterly surveys (Bendik and Dries 2018, Barton Springs Pool Habitat Conservation Plan, City of Austin 2013).
- Restoring conduits intercepted/cut-off by well drilling.

1.4.1.4 Endangered Birds

The federally listed endangered Golden-cheeked warbler (*Setophaga chrysoparia*) and the recently delisted but vulnerable Black-capped vireo (*Vireo atricapilla*) both find suitable habitat in some of the WQPL management units. Mature woodlands are the preferred habitat of Golden cheeked warbler. The potential impacts of the WQPL land management regime to these species is carefully assessed. Presence/absence surveys are conducted by third-party consultants prior to land management activities to ensure no adverse impacts.

1.4.1.5 Mammals

Feral hogs (*Sus scrofa*) are present on some of the WQPL management units and represent the biggest mammalian threat to the ecosystem in these areas. These invasive animals are the descendants of wild European hogs (introduced for hunting) and escaped domestic swine. Hogs are generalist omnivores, feeding primarily on vertebrates, invertebrates, the eggs of ground-nesting birds, forbs, roots, and mast, particularly in woodland areas. Their omnivorous diets and rooting behavior lead to substantial vegetation disturbance, and these prolific animals may adversely affect other wildlife. Their rooting behavior can also substantially impair riparian areas. Disturbed areas are prone to erosion and may experience shifts in plant species composition, which can lead to adverse water quality effects in the recharge and contributing zones and, therefore, the discharge at Barton Springs (Davis and Schmidly 1994). On sites where their presence is evident, hunting or trapping should be used to eliminate this species to the extent possible.

Feral cats (*Felis catus*) and dogs (*Canis lupus familiaris*) may also be problematic in the WQPL. Predation by cats is a significant cause of wildlife mortality, particularly rodents, reptiles, and birds (Schaefer 1999; Bonnaud, et al. 2011), and diseases carried by cats may also pose serious threats to native species. The damaging effects of cats on wildlife are particularly severe in "islands" of wildlife habitat and other open spaces near urban areas (Jurek 1994; Medina et al. 2011). Because feral cats are rarely territorial, their populations can result in high predation rates (Coleman et al. 1997), which has globally contributed to extinction of many animal species (Jurek 1994; Loss and Marra 2017). Free-roaming or feral dogs may be less of a problem on the WQPL from an ecosystem function standpoint. Although they are known to kill ungulates, rodents, reptiles, and birds, typically they do not significantly affect native wildlife populations. (Home et al. 2018; Schaefer 1999).

1.4.2 Floral Species

1.4.2.1 Desired Rare Plant Species

Of the 42 plant species classified as rare, threatened, or endangered by the Texas Parks and Wildlife Department, 13 have been documented on the WQPL (Table 3). The continued presence of these species is consistent with the existing land management regime and none of these species merit special protective measures. Shade dependent species, such as *Onosmodium helleri*, *Clematis texensis*, *Hexalectris nitida*, and *Tridens buckleyanus* could potentially be threatened by canopy reduction treatments, however they occur in woodlands that are not planned for these treatments. Full sun species, including *Liatris glandulosa*, *Physaria engelmanii*, and *Desmanthus reticulatus*, could be threatened by woody plant encroachment if canopy reduction treatments were to cease, however, they all occur in areas that are planned for maintenance with prescribed fire and/or woody plant thinning treatments. All other species tolerate the variable light conditions that characterize the WQPL's disturbance-dependent savannas. A comprehensive inventory of listed plant species has not been conducted on the WQPL in over twenty years, during which many new tracts have been acquired, so Table 3 may not be exhaustive.

According to anecdotal evidence by WQPL staff biologists, *Festuca versuta* has increased on many sites, particularly those treated with thinning treatments and prescribed burns.

Table 3: Rare, threatened, and endangered plant species on the Water Quality Protection Lands.

Latin Name	Common Name	Global Rank	State Rank
Brickellia dentata	Gravelbar brickellbush	G3G4	S3S4
Chaetopappa effusa	Spreading leastdaisy	G3G4	S4
Liatris glandulosa	Glandular gay-feather	G3	S2
Berberis swaseyi	Texas barberry	G3	S3
Onosmodium helleri	Heller's marbleseed	G3	S3
Physaria engelmannii	Engelmann's bladderpod	G4	S3
Amorpha roemeriana	Texas amorpha	G3	S3
Desmanthus reticulatus	Net-leaf bundleflower	G3	S3
Clematis texensis	Scarlet leather-flower	G3G4	S3S4
Hexalectris nitida	Glass Mountains coral-root	G3	S3
Festuca versuta	Texas fescue	G3	S3
Tridens buckleyanus	Buckley tridens	G3G4	S3S4
Argythamnia aphoroides	Hill Country wild-mercury	G2G3	S3

1.4.2.2 Undesirable Invasive and Savanna-Encroaching Plant Species

There are nine common non-native invasive plant taxa on the WQPL: Johnsongrass (*Sorghum halepense*), King Ranch bluestem (*Bothriochloa ischameum var. songarica*), Kleberg bluestem (*Dicanthium annulatum*), Silky bluestem (*Dicanthium sericeum*), Bermudagrass (*Cynodon dactylon*), plumeless thistles (*Carduus* spp.), Chinaberry (*Melia azedarach*), Chinese pistache (*Pistacia chinensis*), and Tree of Heaven (*Ailanthus altissima*). Salt cedar (*Tamarix* spp.) and privet (*Ligustrum* spp.) were once locally invasive but have been nearly eliminated from the WQPL through past control efforts. Of less concern among non-native species are Chinese tallow tree (*Triadica sebifera*), Scarlet firethorn (*Pyracantha coccinea*), Dallisgrass, (*Paspalum dilitatum*), Malta star-thistle (*Centaurea meltensis*), Chinese photinia (*Photinia seratifolia)*, and Heavenly bamboo (*Nandina domestica).* Although these species are present at low levels, and they do not warrant intensive control efforts aimed at eradication (e.g., Ewel and Putz 2004), though they should be monitored to ensure that they do not become more widespread.

Invasive species only present a threat to water provisioning and biodiversity when they dominate a system to such an extent that they outcompete desirable savanna grasses, increase erosion, and/or contribute to severe wildfire risk (Mack et al. 2000, Pejchar and Mooney 2009). Presently, the only non-native invasive species that meets this criterion is King Ranch Bluestem, which alone comprises 40% of all plant species observations from permanent vegetation transects on the WQPL that have been monitored for over 15 years. Fortunately, King Ranch Bluestem is susceptible to high mortality from growing season fires, making prescribed summer fire a key tool for controlling it (Novak et al. 2021).

There are four native savanna-encroaching species of concern: Ashe juniper (*Juniperus ashei*), mountain laurel (*Sophora secundiflora*), lanceleaf sumac (*Rhus lanceolata),* and honey mesquite (*Prosopis glandulosa*). Like some invasive species, these native tree and shrub species have reached high local abundances in former savannas of WQPL due to overgrazing and fire exclusion (i.e., woody encroachment), to the detriment of native plant diversity (Novak et al. 2021). Note that Ashe juniper, while a valued species in old-growth woodlands (Diamond 2015), is undesirable in savannas, where it can suppress native grasses and contribute to severe wildfire risk (i.e., crownfire during seasonal droughts, McCaw et al. 2018).

1.5 Archaeological Sites

Future development will have to consider both direct impacts (e.g., trails, pipelines, buildings etc.) and indirect impacts (e.g., increased public access) to cultural properties. Most of the sites that have been recorded have been surficial and/or shallowly buried, making them particularly vulnerable to impacts while deeply buried cultural deposits may be sufficiently protected from surficial impacts and casual collecting. Conversations with the Texas Historical Commission indicate that land management typical of the WQPL is not expected to impact archeological sites (personal communications, Kevin Thuesen, City of Austin).

1.6 Land Cover Categories

The WQPL's fee title land can be classified into four broad categories based on plant community and management constraints, each of which is described below and the extent of which is shown in the map of each WQPL Management Unit (Figures 24-34).

1.6.1 Savanna Grassland

This land cover category designates large (greater than 3,000 acres), mostly contiguous tracts of land dominated by herbaceous cover. The scale and grass dominance of these areas is conducive to land management interventions that limit woody plant canopy cover below climatic maxima to benefit natural resource objectives such as water provisioning and biodiversity.

1.6.2 Savanna Woodland

This land cover category designates woodlands that do not support Golden-cheeked warblers. These generally have patchy or low herbaceous cover and are dominated by trees greater than 8-inch diameter at breast height. These areas are generally not receptive to grassland restoration but may benefit from limited or patch scale canopy reduction such as from prescribed burns.

1.6.3 Interface Savanna

This land cover category designates smaller (less than 1000 acres) tracts of land that are adjacent to or embedded within urban or otherwise developed areas that are dominated by herbaceous cover. Land management interventions on these sites tend to be constrained due to their smaller size and urban geographic context, which can increase the cost, complexity, and risk associated with each land treatment, and can limit the benefit to natural resource objectives such as water provisioning and biodiversity.

1.6.4 Warbler Woodland

This land cover category designates seasonally-occupied nesting habitat for the endangered Golden-cheeked warbler. Management of these areas must follow the Texas Parks and Wildlife document entitled, “Management Guidelines for the Golden-cheeked Warbler in Rural Landscapes” (Campbell 2003). Golden-cheeked warbler habitat has been identified with presence/absence surveys conducted by private, third-party consultants.

Section 2
General Land Management Considerations

2 General Land Management Considerations

2.1 Restoring Historical Communities

Savannas and forests are biome states (Staver et al. 2011a), where fire, herbivores, and human land management can determine the location of different vegetation types. Prairies and oak savannas of central Texas are examples of ancient grassland ecosystems that occur in the same climate as closed-canopy woodlands (Noss et al. 2015, Bond 2016). Paleoecological evidence indicates that savannas have consistently occupied central Texas for the past 10-18 thousand years (Larson et al. 1972, Nordt et al. 1994, Hall and Valastro 1995, Bousman 1998, Jessup et al. 2003, Cordova and Johnson 2019) and occupied savanna refugia in the North American Coastal Plain during Pleistocene interglacial periods over the past 2.6 million years (Noss et al. 2015). Before the advent of European land management practices, which broadly excluded fire and native herbivores, the region was characterized by more open savannas, and the dense juniper woodlands that are extensive today were more limited in scale (Table 4; Smeins 1980, Smeins 1982, McPherson et al. 1988, Smeins and Merrill 1988, Archer 1989, 1990, Scholes and Archer 1997, Fowler and Simmons 2008).

Table 4. Distribution of endemic plants in the Eastern Edwards Plateau relative to shading. Placement in categories was based on observations by William Carr during field work between 1981 and 2019. See Appendix 2 for the full list of species. The high percentage of endemic plants that prefer sunny environments, and paucity of species in full shade, is consistent with a long history of savanna environments in Central Texas.

Full Shade	Full shade to partial shade	Partial Shade	Partial shade to full sun	No Shade
0	17	9	17	28

In the historical savannas of central Texas, frequent fires and bison grazing played an interactive role in maintaining grassland communities (Fuhlendorf et al. 1996, Fuhlendorf and Smeins 1997a, Fuhlendorf and Smeins 1997b). Fires, ignited by lightning or Native Americans, occurred every 1 to 4 years (Guyette et al. 2012) and contributed to the high diversity of the region's grassland-dependent plants and animals (Noss et al. 2015). Although more fires today are ignited by people than by lightning (Balch et al. 2017), central Texas still experiences high lightning frequency with at least 1 flash/km^2/month between April and September and a peak of 2.1-2.4 flashes/km^2/month in May and June (Novak et al. 2021). The fire-adapted grassland flora of central Texas have existed in North America for at least the past 2 million years and thus far predates the arrival of humans 12,000 years ago (Noss et al. 2015). Fire is not the only historical reason for the existence of savannas in Texas. Bison and other extinct megafauna (both grazers and browsers) migrated to feed on recently burned areas, which promoted plant diversity and limited woody encroachment (Fuhlendorf et al. 2009). The transition from free roaming native herbivores to fenced livestock has led to the decline of native-grass savannas and the expansion of low-diversity juniper woodlands; but even where savannas have not been replaced by woodlands, mismanaged domestic livestock and fire exclusion have produced many grasslands dominated by invasive species (Smeins 1980, Novak et al. 2021).

Although numerous tools are available for restoring savannas toward their historical condition, it is important to view savanna restoration as a process and not a one-time event (Buisson et al. 2019). Once restored, grassland and savanna ecological states require routine management, such as application of prescribed fire, to prevent the recurrence of woody plant dominance (Smeins 1982, Novak et al. 2021, Ansley et al. 2021). Because the WQPL is characterized by a mosaic of savannas and woodlands across uplands, riparian areas, and slopes, different ecological reference models (i.e., historical plant communities) should guide restoration on different sites.

Often overlooked ecosystems during savanna restoration are riparian corridors because they frequently include a different guild of woody species. In the Edwards Plateau, these species can include Pecan and Hickory (*Carya* spp.), American Elm (*Ulmus americana*), and Bald Cypress (*Taxodium distichum*). These communities also support some of the most robust populations of grassland species, including Big Bluestem (*Andropogon gerardii*), Silphium (*Silphium radula*), and Western Ironweed (*Vernonia baldwinii*), that are still found today. The mesic conditions associated with riparian habitats sometimes lead to speculation that these areas were consistently wooded prior to non-indigenous settlement; however, other factors may limit the extent of woody cover in riparian areas. For example, fluctuations between extreme wet and dry periods and disturbance from flooding and herbivory have been shown to inhibit woody growth in seasonal creek channels and riparian flood plains and facilitate diverse ancient grassland communities throughout the southern U.S. (Noss 2012). Relict tallgrass savannas dominated by Switchgrass (*Panicum virgatum*), Eastern gamagrass (*Tripsacum dactyloides*), and Bald Cypress (*Taxodium distichum*) often occur on channel bottoms and floodplains. Such areas are characterized by alternating wet and extended dry conditions, intermediate light availability, and high herbaceous plant diversity.

2.1.1 Species Diversity in Central Texas Savannas

Savannas of central Texas are often conceptualized as transitional between the Blackland Prairie and Edwards Plateau ecoregions. Blackland prairie is a part of the Grand prairie, which occurs from the San Antonio area, east of what is now the Interstate 35 corridor, to the Red River (Collins et al. 1975, Riskind and Collins 1975, Diamond and Smeins 1985, Diamond and Smeins 1993, Windhager 1999). Grasslands of the Blackland prairie are floristically similar to other tallgrass prairies in North America, dominated by deep-rooted perennial warm season grasses and almost entirely lacking trees, except along riparian corridors (Dyksterhius 1946, Weaver 1954, 1968, Riskind and Collins 1975). Savannas of the Edwards Plateau are grassy communities composed of many of the same species found in Blackland Prairie (Landers 1987), interspersed with widely separated motts (clumps) of oaks and juniper primarily restricted to steep slopes (Buechner 1944, Smeins et al. 1976, Knight et al. 1984, Fowler 1988). As with all disturbance-dependent mesic savannas, woody species in both the Blackland Prairie and savannas of the Edwards Plateau are limited by a combination of frequent fire and high intensity short duration grazing by bison (Fuhlendorf et al. 1996, Fuhlendorf and Smeins 1997a, Fuhlendorf and Smeins 1997b).

In savannas of central Texas, like many savannas globally (Parr et al. 2014), plant diversity is concentrated in the herbaceous layer of grasses and forbs. For example, over 492 species have been documented on the Onion Creek Management Unit of the WQPL (Watson 2020), and a remnant of the Blackland prairie in Round Rock was documented to have over 200 species (Gee and Campbell 1990). A more recent study conducted on WQPL identified six old-growth grassland sites that supported 95 species per 1000 square meters and 20 plant species per square meter (Novak et al. 2021). Despite a history of overgrazing, and thanks in part to an active prescribed fire program that promotes plant diversity (Novak et al. 2021), the Lady Bird Johnson Wildflower Center, which is adjacent to some of the WQPL properties, supports 302 native plant species on its 165 acres.

In addition to the above studies, the USDA Natural Resources Conservation Service (2013) has described each of the ecological sites contained within the WQPL (Table 2). Each ecological site description includes the ecosystem states that sites can support and identifies the historical plant community, which should serve as the reference for restoration (Buisson et al. 2022). The descriptions list the common species and their approximate percentage of biomass that would compose the site in each state (typically 20 to 30 species).

2.1.2 Native Seeds: Availability, Harvesting and Sowing

Much of the WQPL needs to be seeded with savanna species to promote more rapid recovery of a vigorous herbaceous plant community, as prescribed fire alone is insufficient to recover old-growth grassland communities (Novak et al. 2021, Buisson et al. 2022).

Some species, including many native warm-season grasses that characterize the reference savanna ecosystems, are available in bulk as commercial cultivars at relatively affordable prices. Detailed information about the origin and area of adaptation of cultivars is available from the USDA. These cultivars are selected for traits, such as rapid establishment following disturbance and hardiness to stressors such as drought, freeze, and herbivory, that are desirable for commercial revegetation applications, such as grazing and erosion control and, therefore, will perform relatively well following disturbance treatments like prescribed fire and woody plant thinning. While cultivated traits can be useful where competition with invasive grasses is a factor, they may also hinder establishment and persistence by less competitive species and alleles. Commercial cultivars may therefore limit species and gene diversity if overused. However, some commercial seed suppliers also carry diverse seed mixes and under-represented specialist species that are sourced locally from remnant grasslands. These are more expensive than commercial cultivars and availability is limited. Most seed suppliers will provide reliable information about the purity of their seed products, but many suppliers and consumers of these products are not using them for conservation objectives and may tolerate a certain level of noxious weed contamination. Third-party experts such as Texas A&M AgriLife extension agents and members of professional organizations, such as the Society for Ecological Restoration, may be able to provide additional advice about contamination risks from unfamiliar vendors.

The origin of wild-types, area of adaptation of cultivars, and cultivation locality of commercially sourced seed can affect long-term performance under climate change. Seed sourced from the south or west may be pre-adapted to increasing drought and heat stress while seed sourced from the north may be more cold-tolerant and may include otherwise unavailable species. Seed produced in other climates may provide a layer of protection against contamination by locally noxious germplasm, but also has the potential to introduce newly-invasive germplasm to which the local landscape was not previously exposed.

Another source of seed is from the local landscape by volunteers, staff, and other collaborators. Mechanical harvesters can improve collection efficiency, but also produce substantial amount of chaff and are vulnerable to contamination by noxious or non-target species. Hand-collection is appropriate for high-value species, and the relative inefficiency of hand collection can be offset with large group size or frequent visits. Seed collection can be a popular recreational, educational, and service activity for the public.

Seeding with a mechanical no-till seed drill tractor attachment improves germination compared to other methods. However, suitability of this method is limited by site conditions such as soil exposure, steep terrain, shallow soil, and obstacles such as rocks and woody plants. Hand-broadcasting is applicable on sites that are not accessible or appropriate for a seed-drill. Raking improves efficacy for hand-broadcast seeding by scarifying soil surfaces, displacing duff or other plant litter, and otherwise improving soil contact, and may be implemented prior to and/or after seed application.

Seeds of grass can be sown in the spring, fall, or winter. Many grasses release their seed in the late summer or fall, especially following summer burns, so seeding at that time mimics their natural cycles. This allows the seed to be naturally weathered if necessary. However, seed sown in the fall has a greater chance of being eaten, washed, or blown away. Most warm season grasses can also be sown in the early spring which reduces the risk of seed predation or loss to the elements, but additional processing may be necessary prior to seeding. In general, forbs should be sown in the fall.

2.1.3 Cattle Versus Bison

Grasses co-evolved with herbivores, and the drier more continental climate during the Pleistocene led to the dominance of Chlorideae and Andropogoneae grasses and the appearance of bison and sheep on the North American plains (Stebbins 1981, Retallack 2007). Extensive herds of bison reportedly occurred throughout the Southern Plains up to 1900 (Lincecum and Phillips 1994; Smeins 1980). With increasing settlement in Texas from 1700 onward, native grazing and browsing herbivores transitioned to free ranging and eventually confined exotic livestock (Smeins 1980). The removal of grazing pressure through the elimination of the native herbivores, followed by initial low stocking rates of domestic cattle during several years of abundant rains (1874 to 1884), created more forage than could be utilized (Smith 1899). However, following this period, increased settlement and higher stocking rates decreased herbaceous productivity, and resulted in an increase of brush species, especially mesquite, prickly pear, and juniper (Smith 1899; Smeins 1984).

It has been widely reported that the diet and foraging behavior of sedentary cattle have had a significantly different impact on grasslands than those of the former large herds of free roaming bison (Allred et al. 2011, Kohl et al. 2013). Migrating bison produced short duration but very intense grazing events, often preferring open grassland areas that had recently burned, after which grazed areas often had several years to recover between bison grazing events (Raynor et al. 2017). On the other hand, domestic cattle that continuously graze across an entire property throughout the year cause continual disturbance on rangelands, of spatially and temporally varying intensity (Teague et al. 2013, Teague and Kreuter 2020). Continual grazing leads to overgrazing of preferred forage species in preferentially selected areas even at moderate to light stocking rates; under these conditions, populations of palatable species decline, and bare patches emerge at a local scale, which in turn aids the spread of woody species by reducing competition between woody and herbaceous species (Walker 1993; Archer and Scholes 1997, Teague and Kreuter 2020). Cattle select different diets from bison, which can have dramatic difference on vegetation especially during episodic drought. (Kohl et al. 2013). For example, the spread of mesquite throughout central Texas has been largely attributed to the ingestion of mesquite pods and consequent defecation of seeds by cattle and the differing grazing patterns and distribution of cattle and bison (Brown and Archer 1989). Specifically, the more widespread distribution of cattle as a vector of dispersal, combined with reduction of fire frequency, which in top-killing mesquite individuals retards pod production, has caused increased establishment of mesquite. Ultimately, to restore grasslands in North America to pre-settlement conditions in the face of climate changes, herbivory by grazers such as bison should be considered integral to grassland management (Allred et al. 2011, Fuhlendorf et al. 2018). Accordingly, reintroduction of bison to the WQPL may be practically difficult or impossible to achieve.

2.2 Management Techniques

2.2.1 Management of Open Grasslands and Savannas

2.2.1.1 Prescribed Fire for Maintenance

Savannas of central Texas require frequent fires for maintenance. Without fire, fire sensitive trees and shrubs increase in abundance, leading to woody encroachment (Taylor et al. 2012). Because of the huge effort required to restore savannas after replacement by woodlands (Buisson et al. 2019), it is paramount that existing savannas burn every 1-4 years (Guyette et al. 2012, typically during the late spring and summer (April through September), which is thought to be the historical (lighting) fire season (Novak et. al., 2021).

Burning on the WQPL is achieved through the application of prescribed fire, which is the systematically planned use of burning to achieve management and safety objectives (Weir 2009). In Texas, prescribed fire is one of the most important processes available for land managers to limit woody encroachment (Taylor et al. 2012), increase forage (Limb et al. 2011), reduce hazardous fuel loads (Waldrop and Goodrick 2012), remove invasive weeds (Simmons et al. 2007), and maintain floral diversity (Novak et al. 2021).

It is important to emphasize that conducting a burn, guided by a detailed burn plan, is just one part of the overall prescribed fire process. Two comprehensive guides to the principles and implementation of prescribed fire are provided by Weir (2009), with a focus on grassland ecosystems, and Waldrop and Goodrick (2012), with an emphasis on woodlands. Other resources for prescribed fire in Texas ecosystems are Landers et al. (1986), White and Hanselka (1989), Scifres and Hamilton (1993), and McPherson (1997).

A key part of the prescribed fire process is the development of a prescription, which details the parameters, or range of conditions, under which burning may occur. Prescriptions may differ based upon conditions related to the ecology of a site, such as grass productivity (which determines the rate of accumulation of fuel), as well as social considerations, such as smoke management (e.g., a site immediately south of a housing development should be burned with a north wind). Some other parameters that are typical in a prescription include, but are not limited to, fuel load, fuel continuity, hours of the day, wind speed and direction, temperature, atmospheric humidity, and proportions of live versus dead fuel.

A key prescription parameter is fire season. Research suggests that summer and winter burns effectively maintain savanna vegetation structure by limiting woody encroachment (Taylor et al. 2012, Novak et al. 2021). Unfortunately, winter burning can promote invasive King Ranch Bluestem, but repeated summer burns, especially burns that occur when King Ranch Bluestem flowers, can result in high mortality (Novak et al. 2021; Ruckman et al. 2012), although reductions in King Ranch Bluestem may not persist (Reemts 2019). This suggests that summer burns should be prioritized in areas where King Ranch Bluestem requires control. Logistically it will be difficult to implement the acreage and frequency of burns needed on WQPL during the summer alone; maintenance burns in any season are preferable to not burning with sufficient frequency to maintain existing savannas.

2.2.1.2 Mowing and Haying

In savannas where prescribed fire cannot be applied, mowing and haying may be used to mimic some aspects of fire and grazing, although mowing has obvious differences in impact. Mowing is non-selective about species and can be quite effective at controlling woody encroachment when implemented while encroaching trees and shrubs are small. Indeed, many old-growth grasslands globally are managed with mowing and haying (Nerlekar and Veldman 2020). Mowers cut plant material near the ground and redistribute it as litter. This contrasts with prescribed burning, which transfers most aboveground grassland biomass to the atmosphere (in the form of carbon dioxide, water, and nitrogen oxides) and returns nutrients and carbon to the soil in the form of ash and charcoal.

Although mowing can have similar effects as fire (Collins and Gibson 1990, Collins et al. 1998) a long-term concern is that thatch accumulation can smother fire-loving grasses and forbs that are not adapted to thatch coverage (Hiers et al. 2007). Haying (i.e., collecting cut material) is recommended to reduce thatch accumulation and may be financially self-supporting if the hay is traded for the mowing services. If mowing and haying is timed with seed production in grasslands composed of desirable species, this hay may be transferred (with the attached seeds) to restoration sites on WQPL that need seed additions.

Although there are advantages to mowing certain areas on a small scale, mowing should not be viewed as a substitute for prescribed fire to maintain existing savannas. Additionally, given the size and topographical roughness of much of the WQPL, mowing will often be logistically difficult or impossible, and costly in terms of equipment and fuel. One place where mowing may be effectively applied is along the interfaces of the WQPL units and adjacent developed areas. This would facilitate the maintenance of fire breaks and reduce the risk of escaped fire from the WQPL to suburban areas, thereby mitigating wildfire risks.

2.2.1.3 Targeted Grazing

Historically, variation in grazing landscapes caused herds of grazing ungulates to move regularly to satisfy water and nutrient requirements, and in response to fire, predation, and hunting influences (Retallack 2013). Periodic concentrated herbivory led to short grazing periods followed by an absence as herbivores moved across the landscape. Early hunters increasingly affected the landscape by burning areas to open them up, and to attract wild grazers to recently burned areas (Pyne 2001). With the arrival of European settlers, migratory herds of native ungulates were increasingly replaced by sedentary domestic livestock (Provenza 2008; Oesterheld et al. 1992). The season-long grazing and elimination of predators that ensued allowed livestock to freely disperse leading to long-term concentrated grazing of preferred areas (e.g., lower, flatter areas with more palatable and easily accessible plants near water resources) and repeated use of preferred forage species (Fuls 1992; Teague et al. 2004). Some researchers have touted pyric herbivory to simulate historical grazing patterns of free-roaming grazers and to enhance the diversity of some threatened and endangers species, notably grassland birds (Fuhlendorf et al. 2006). With patch burning and continuous grazing that characterize pyric herbivory, newly burned patches attract heavier use while relieving previously burned areas of defoliation. However, uncontrolled grazing on burned patches and under-utilization of unburned areas can reduce plant biomass and increase bare ground that becomes susceptible to erosion. Numerous grazing management approaches have been recommended to control localized overgrazing; collectively they are often called rotational grazing and they combine grazing frequency, duration, and deferment with strategically located mineral blocks and water points, to move livestock across the landscape (Holechek et al. 2010). Many of these approaches have not demonstrated improved grassland conditions and animal performance (Briske et al. 2008), although some of the premises of these findings have been criticized (Teague et al. 2013). More recently, an increasing body of research is showing that adaptive multi-paddock (AMP) grazing management is effective for restoring and maintaining the ecological function of grazing lands (Teague and Kreuter 2020). This approach uses short grazing periods to ensure the retention of plant cover for rapid plant regrowth and soil protection, and it provides long plant recovery periods thereby reducing bare ground while maintaining productive grass composition on both burned and unburned areas (Teague et al. 2010). Importantly, it adjusts stock numbers and grazing periods to match available forage biomass (Provenza 2008; Teague et al. 2013; Wang et al. 2017).

While AMP grazing globally shows considerable promise for the restoration of previously degraded grasslands and savannas (Teague and Kreuter 2020), widescale and long-term use of livestock grazing on the WQPL is likely incompatible with its open space conservation goal for producing high quality recharge water for the Barton Springs segment of the Edwards Aquifer. The reasons are: (1) the substantial cross fencing generally required for this approach to grazing management, and (2) concentrated fecal deposition by livestock could lead to increased surface runoff contamination. However, contract herding, or increasingly feasible virtual fencing may be options for using livestock strategically to reduce fine fuel loads at critical times in areas where prescribed fire cannot be readily applied, e.g., near housing developments or riparian areas and wetlands with sensitive vegetation. Such targeted grazing has been used widely to address specific land management objectives (Bailey et al. 2019), and it may be an option for use on the WQPL when other herbaceous biomass removal options are not feasible. An important distinction of grazing compared to burning and mowing is that herbivores are selective when defoliating plants and return nutrients to the soil through defecation.

2.2.2 Management of Woody Encroached Areas

2.2.2.1 Prescribed Fire for Restoration

Fire exclusion, particularly when coupled with a history of overgrazing, has caused woody plant encroachment throughout Texas (Smeins 1984), which has led not only to loss of herbaceous productivity and declines in plant diversity, but has also altered hydrological characteristics of watersheds (Thurow and Carlson 1994). After chronic fire exclusion, considerable effort is required to restore woodlands and shrublands to a grassland or savanna state (Hanselka et al. 1996, Hanselka et al. 1999) mainly due to the biological characteristics (e.g., resprouting) of the prominent encroaching species, and the way trees alter ecosystem flammability (e.g., woody encroached areas lose native grasses that are important to carrying surface fires, Nowacki and Abrams 2008).

Prescribed fire should be the preferred process used to reduce woody cover during savanna restoration. Ideally, prescriptions for reducing woody cover will be written to ensure fire intensities are high enough to result in tree mortality, top-kill, and crown scorch, which improve conditions for the growth and re-establishment of savanna grasses and forbs. As such, it is often necessary to burn under hotter and drier conditions than needed for maintenance burns in existing savannas (see Section 2.2.1.1). Burning under extreme conditions is quite effective (Ewing et al. 2005, Twidwell et al. 2016), but doing so is challenging when trying to balance ecological goals with fire safety.

Fortunately, trees and shrubs do not need to be killed during fire, but rather damaged or top-killed to make restoration progress (Hoffmann et al. 2009, Ansley et al. 2021). It is generally also impractical to revert a woodland to a grassland in just one prescribed burn and burns that reduce woody vegetation incrementally should be viewed as progress toward savanna restoration. However, for fire to penetrate dense woody encroached areas, managers will need to burn during dry conditions, albeit less extreme than conditions needed for maximum tree mortality (e.g., Twidwell et al. 2016). Fire season is an important consideration to achieve sufficiently high fire intensity to control encroaching woody plants. Typically, restoration burns will need to be applied in summer, which has been demonstrated to be superior to fall burns for woody control (Novak et al. 2021).

Restoration fire return intervals may be shorter or longer than maintenance return intervals (2-4 years) depending on several factors, primarily the rate of woody plant regeneration and the rate of herbaceous fuels accumulation required for prescribed burning. Restoration burns to recover savannas lost to woody encroachment should be as frequent as possible (1-3 years), so long as fuels permit effective spread of sufficiently intense fire. Areas with shallow soils will take longer to accumulate fuel and may require longer return intervals (3-6 years) even during the restoration phase, particularly if drought limits fuel production. All areas should be annually monitored for plant composition, vegetation structure, and soil conditions, and the results of these examinations should be used to determine appropriate fire prescriptions. For further discussion of this topic, see Section 4.1.1.

2.2.2.2 Mechanical Control of Trees and Shrubs

Where woody encroachment has severely diminished fine fuels, it may be necessary to cut trees and shrubs with chainsaws. The goal is to open the canopy to allow light penetration, increase the productivity of existing grasses, and encourage herbaceous plant establishment (often from seeding, see Section 2.1.2). Felled trees and shrubs may be left in place to avoid soil disturbance (Veldman and Putz 2010). Furthermore, hand cutting can be more targeted than other mechanical treatments, which is particularly important in restoration of savannas where certain fire-adapted tree species are desirable (e.g., post oak), or habitat for endangered species requires thinning (e.g., Golden-cheeked warblers). Despite the ecological advantages, cutting can require significant labor and may be cost-prohibitive for large areas. For this reason, cutting could be strategically planned along boarders of existing savannas or in narrow strips (i.e., corridors), which contribute to incremental restoration of woodland to savanna and promote fire spread (Brudvig et al. 2012).

Cutting shrubs and trees converts live coarse fuels into dead woody debris (felled trunks, limbs, and branches, a.k.a. slash). Such coarse fuels dry and burn differently than fine fuels in savannas and require special attention in prescribed fire. Because woody debris can burn and smolder for hours or days, prescriptions should be written with special attention to the fuel load and moisture content of coarse fuels during woodland-to-savanna restoration (Waldrop and Goodrick 2013). If slash from thinning treatments is scattered amongst perennial warm season grasses, low intensity surface fires will be adequate to consume scattered slash from prior thinning treatments. Under these conditions, the initial burn substantially reduces but does not completely consume slash. After about three burns, however, residual woody debris usually becomes negligible. Slash may persist, even if it is exposed to prescribed fire, if grass cover is poor; however, that condition is typically patchy and only merits additional effort along burn unit boundaries. If slash loads are high and grass loading is poor throughout significant areas of a burn block, substantial interior labor may be needed to drag and pile slash and to set interior ignitions.

Other mechanical methods involve the use of machinery (e.g., skid steers) to cut or grub vegetation. Such methods should be implemented carefully to avoid compounding problems, such as accumulation of deep mulch (greater than 3/4 inches) that impedes grass growth, multi-stemmed resprouting that can inhibit fire, and spread of invasive seeds. To avoid such problems, methods such as roller chopping can be effective when planned in conjunction with other brush control techniques (prescribed fire in particular) (Hanselka et al. 1999). Preferred mechanical removal is the use of skid steer-mounted tree shears, which cut woody plant stems at the surface without excessive soil disturbance, or mulching heads which grind plant material off above the soil surface. Avoiding the stacking of brush can substantially decrease soil compaction associated with repeated driving over the same ground to stack cut plant matter. WQPL's current specifications require cutting at ground level and shattering the cut brush to a height of less than two feet. This decreases soil compaction and simultaneously decreases the price for such work.

2.2.2.3 Chemical Control of Trees and Shrubs

Brush can also be reduced by using herbicides, which is often the most efficient method for controlling certain brush species that will resprout if cut or top-killed without herbicide thereby compounding the original problem (Hanselka et al. 1996, Hanselka et al. 1999). WQPL staff, in conjunction with Watershed Protection Department staff, have developed an Integrated Pest Management Plan (IPM), which includes appropriate chemical removal practices that increase the effectiveness and efficiency of work, and which provides guidelines for treating undesirable species in a variety of environments.

2.2.2.4 Targeted Browsing

Targeted herbivory has been used to address numerous rangeland management challenges (Bailey et al. 2019). Specifically, goats have been found to selectively browse both resprouting and non-resprouting plants. In the Edward's Plateau, they have been found to browse twice as much Ashe juniper as redberry juniper, and they prefer juniper seedlings and regrowth to mature juniper plant matter (Treadwell et al. 2021). Additionally, it has been found that juniper intake is a heritable trait, that Spanish goats consume more juniper than Angora and Boer goats, that conditioned goats consume more juniper than unconditioned goats, and that conditioning can last for extended periods, especially when preferred herbaceous forages decreased (Dietz et al. 2010; Treadwell et al. 2021). While juniper can constitute a significant portion of goats' diets, they also need other dietary components (Riddle et al. 1999). In the Edward's Plateau, the juniper content in the diet of commercial meat goats was found to range from 20% to 50%, with the average goat (100 pounds) consuming around 0.6 pounds of juniper foliage per day (Treadwell et al. 2021); however, this high consumption of juniper is not ubiquitous (Fajemisin et al. 1996).

Targeted browsing by goats during periods when encroaching woody plants are most susceptible to consumption could be used to reduce the vigor and cover of invasive non-resprouting species (e.g., Ashe juniper) and resprouting species (e.g., live oaks and Texas persimmon) (Fuhlendorf et al. 1997). Periods when this would be most effective include spring when new shoot growth is greatest, late summer when availability of preferred herbaceous plants is limited, and a year or two after prescribed fire when new plants emerge. The best suited areas would likely be where WQPL properties border neighborhoods and where the potential for using prescribed fire is limited due to the greater risk of fire escapes. Areas with mountain laurel, which may be toxic to goats if consumed in large quantities, should be avoided.

Advantages to using goats to control resprouting species include reduced use of herbicides and less soil disturbance than would result from mechanical control methods. Additionally, goats can access areas, such as steep slopes, that are difficult to treat by other means. Disadvantages include the need for fencing, water, additional food, protection from predators, medical care, and labor. To avoid these challenges, a contractor could be used to assume responsibility for goat management including transportation, fence installation and removal, providing additional food, water and medical care, and protection from predators. Contractor costs will depend on bids based on individual situations. In the contract, it would be important to note that goats will be used primarily as a tool for brush management and that the arrangement is not intended to improve the goats for market; without supplemental feed, goats may gain limited weight or lose weight. The goats would be placed in areas the WQPL land manager deems appropriate. Additionally, strict accounting of incoming and outgoing goat numbers would have to be provided and all goats would have to be removed from the property following the completion of work. A contractor template for such a service is provided in Appendix 3.

2.3 Wildlife Population Management

2.3.1 White-Tailed Deer and Blackbuck

White-tailed deer population density in the Edwards Plateau ecoregion is generally high (Armstrong and Young 2000), and likely limits oak regeneration (Russell and Fowler 2004) and consequently degrade nesting habitat for the Golden-cheeked warbler (Andruk et al. 2014). In addition, high deer population density can negatively impact native plant diversity and is a general problem throughout most natural areas in North America, where large native predators have been largely eradicated for over a century. Herd management (culling or sterilization) by commercial contractors may be beneficial to ecosystem diversity, resilience, and function. However, earlier efforts to manage deer populations on the WQPL, which were conducted between 2001 and 2013, had mixed results. Where successful, it was anecdotally observed that deer culling efforts corresponded with increasing woody plant cover, though the strength of this effect is not known (Kevin Thuesen, personal communication, City of Austin). Therefore, because White-tailed deer are predominantly browsers (although they also consume substantial amounts of forbs and mast), high deer populations may help limit woody plant encroachment. It is thus consistent with the WQPL land management goal of reducing woody plant cover to refrain from herd management at the present time. Since deer were last managed on the WQPL, most properties boundaries have had high fencing installed and thus deer management efforts may prove more effective in the future because immigration will not add to internal deer populations. If woody plant cover can be maintained at target levels with reduced intervention in the future, it may be beneficial for plant diversity and related ecosystem functions and services to reconsider herd management on the WQPL.

2.3.2 Feral Hogs and Other Feral Animals

Based on Timmons et al.'s (2012) estimated statewide average feral hog population density of 14 animal hogs per square mile, the 19 square miles of WQPL properties would equate to a feral hog population of about 266 animals. To reach a stable population, it has been suggested that an annual harvest rate of 66% (i.e., about 175 hogs per year on the WQPL) is necessary (Timmons et al. 2012). The most used off-take methods for feral hog population control are trapping and shooting. Currently, the WQPL uses corral traps that can be monitored with a game camera and triggered remotely when numerous animals enter the trap, where they are dispatched. Other effective options include shooting them from the ground or in a helicopter, and sterilization or poisoning using bait placed in hog-accessible enclosures. However, these methods are unlikely feasible for the WQPL due to high cost, limited efficacy, and risk of non-target animal species accessing poison or sterilization-drug laden bait. Therefore, the current trapping method is likely the most feasible for the WQPL although this approach to reducing hog numbers may be insufficient to reach the require off-take number.

Feral or free-roaming domestic cats or dogs do occur on the WQPL properties but represent few problems. When they are seen, the City of Austin Animal Control be informed.

Section 3
WQPL Land Management Guidelines and Goals

3 WQPL Land Management Guidelines and Goals

3.1 Assumptions Guiding the Management Plan

In May 1998, Proposition 2 was approved by City of Austin voters and provided $65 million in utility revenue supported bonds for the acquisition of land in fee title and easements in the Barton Springs contributing and recharge zone to maintain the safety of part of the City's water supply. In November 1998, the passage of Proposition 8 provided an additional $8 million for making improvements and expansions to the City's waterworks system. Additional approved propositions in 2000 and 2006 provided $13.4 million and $50 million, respectively, for constructing and installing improvements and facilities for flood control, erosion control, water quality maintenance, and stormwater drainage, and acquiring additional fee title land and easements in the Barton Springs contributing and recharge zones to conserve the region's water quality. In 2012, the passage of another successful proposition produced $30 million to enable the City of Austin to purchase additional land and conservation easements in the Barton Springs contributing and recharge zones to protect water quality, open space, and critical baseflows and provide a contiguous buffer where tracts are located next to existing protected land. Finally, Proposition D in 2018 led to $72 million to purchase land and conservation easements on properties in Austin's southern watersheds that feed the Barton Springs and the Colorado River to protect the quality and quantity of water in Austin's aquifers, springs, greenbelts, and parks, to mitigate flooding, and to preserve open space in perpetuity.

Aside from the primary purpose of acquiring these properties and conservation easements to protect the quantity and quality of recharge water that subsequently emerges at Barton Springs for the sake of the swimming pool and the endangered salamanders that exist there, the Barton Springs segment of the Edwards Aquifer is also the primary source of drinking water to thousands of people (BSEACD; https://bseacd.org/about-us/history/). If Austin Water pursues indirect potable reuse through Lady Bird Lake, considered to be the most economical way of increasing future water supply in the Water Forward plan adopted by Austin Water in 2018, Barton Springs' importance for providing drinking water will increase further (Water Forward 2018).

3.2 Managing Land for Water Quality and Quantity

Savanna restoration is not only good for conserving the historical biodiversity of central Texas, but also the best management technique for the optimization of water quality and quantity. However, many sites across WQPL are stable oak/juniper and juniper woodlands that would require significant energy and expense to restore to savannas.

The WQPL consist of areas deemed critical for watershed protection in Travis and adjacent Hays counties, Texas. One of the primary results of preserving this land is the permanent removal of these properties from consideration for development. A quantitative difference in water quality and quantity between properties with and without development has been widely recognized (Rentachintala et al. 2022; Zang et al. 2019; Wagner and Breil 2013). The following impacts have been associated with increased levels of impervious cover and land development, all of which compromise the quality and quantity of water: water quality degradation, increased storm runoff and flooding, erosion, stream channel enlargement, and baseflow reduction (Gurnell et al. 2007). Many of these impacts can be reduced through a combination of engineered structural controls and careful site design. However, the most direct and permanent means of accomplishing water quality and quantity protection for creeks and aquifers is to maintain the watersheds contributing to these streams and aquifers in an undeveloped and properly managed condition.

The first step has been accomplished by the WQPL properties that are protected from development. This alone will accomplish much toward achieving water quality and quantity goals by preserving pervious ground cover and ensuring the basic hydrologic regime is maintained. The second step requires implementing land management that supports properly functioning ecosystems that provide many ecosystem services, including the optimal supply of high-quality water. Intact ecosystems exert control over limiting resources (soil, water, nutrients, organic materials) and primary ecosystem processes (hydrology, nutrient cycling, and energy capture) (Whisenant 1999). Ecosystem function can be damaged through direct alteration of ecosystem structure (e.g., adding roads or removing critical functional plant groups), or by the alteration of the natural disturbance regime (e.g., fire suppression in a fire adapted system). The goal of land management is to restore ecosystem function so that the system can better provide ecosystem services.

Wildlands are less modified than developed areas, having few roads, buildings, artificial drainage systems or other impervious surfaces that affect hydrologic cycles in suburbs and cities. However, because the type and pattern of woody vegetation also affects streamflow and groundwater recharge in water limited environments (Wilcox et al. 2022), even ranching activities can alter natural hydrologic systems. Beginning in the late 1800s, livestock overgrazing, and fire suppression led to the transformation of much of the Edwards Plateau landscape and the balance between vegetation types (specifically between grasses, forbs, and woody vegetation) was altered (Van Auken 2000). With these changes came significant changes to the groundwater regime (Wilcox and Huang 2010, Wilcox et al. 2008) These negative changes are not irreversible, however, and much research has been done to find the best ways of restoring ecosystem function in savanna ecosystems.

The relationship between woody plant cover and the water cycle is complex and depends on several factors including precipitation, depth to groundwater, soils, underlying geology, and landscape physiography (Wilcox et al. 2022, Acharya et al. 2018). Considerable research on the ecohydrology of woody plants on drylands conducted in the last 15 years can inform decisions regarding woody plant management to achieve water supply and quality objectives. Fundamentally, woody plants can alter the hydrologic cycle on drylands by modifying evapotranspiration and soil infiltrability, with the relative importance of each depending on annual rainfall. In general, the higher the rainfall, the more potential for woody plants to reduce groundwater recharge because of increasing evapotranspiration; however, as annual rainfall diminishes, changes to soil infiltrability become more important. Understanding these two driving mechanisms and how they vary with climate is critical for interpreting what on the surface appears to be conflicting research findings.

Woody plant encroachment has modified grasslands and savannas across the Southern Great Plains. Recent work has explored the ecohydrological ramifications of these changes in several ecoregions including Cross Timbers and Tall Grass Prairie in Oklahoma, and Post Oak Savanna, South Texas Plains, Edwards Plateau, and Rolling Plains in Texas. Results from these studies are crucial for informing vegetation management in the WQPL.

Cross Timbers and Tall Grass Prairie in Oklahoma: Research in this ecoregion has advanced knowledge about how woody plant encroachment is affecting the ecohydrology of this region. Findings are relevant to the WQPL because average annual rainfall (around 1000 mm/year) and the aridity index (around 0.5) are comparable to Austin. Recent estimates indicate that woodlands are expanding by about 8% a year or about 40 km^2/year (Wang et al. 2017; Wang et al. 2018a) in the Oklahoma Cross Timbers. An active research program within the Cross Timbers region has generated much of the current knowledge concerning the ecohydrological implications of eastern red cedar (*Juniperus virginiana*) proliferation in the Central Great Plains (Zou et al. 2018). In the past decade in particular, this research has provided detailed insights into the negative effects (including drier soils, less groundwater recharge, and lower streamflow) of the encroachment of this species into grasslands and savannas (Zou et al. 2014; Zou et al. 2015; Zou et al. 2016; Acharya et al. 2017a; Acharya et al. 2017b; Qiao et al. 2017). These ecohydrological changes are being driven largely by higher transpiration and interception losses in the juniper woodlands (Caterina et al. 2014; Wang et al. 2018b; Torquato et al. 2020). Modeling exercises and historical streamflow records suggest that these smaller-scale changes will result in reduced streamflows at larger watershed scales (Zou et al. 2016; Starks and Moriasi 2017).

Post Oak Savannas in Texas: Recent work in this region is also highlighting how thicketization (principally by oak, juniper, and yaupon) is significantly reducing groundwater recharge. These results are also applicable to the WQPL because of similar annual rainfall and aridity index. Although relatively few field studies have evaluated vegetation change effects on recharge rates in the Carrizo–Wilcox aquifer region, modeling work by Keese et al. (2005) found that where the dominant vegetation consists of deep-rooted trees, groundwater recharge is significantly lower than where shallow-rooted grasses dominate. These modeling predictions have recently been corroborated by field research near Milano, Texas (Basant 2022), where average annual rainfall is about 930 mm/year, and the aridity index is 0.5-0.6. The chloride mass balance approach was used to compare long-term recharge rates in thicketized woodlands with those in open pastures. The rate of deep drainage in the woodlands was only around 1 mm/year compared with 127 mm/year in the open pastures. While these results need to be verified at more locations, they strongly suggest that thicketization dramatically reduces groundwater recharge.

South Texas Plains and Rolling Plains in Texas: At the drier end of the spectrum, where annual rainfall is 600 mm or less, woody plants also alter ecohydrological processes but, in this case, largely because of soil infiltrability changes. These findings have been borne out from work in both the South Texas Plains and the Rolling Plains ecoregions. In interpreting these findings, it is important to recognize that historic overgrazing and subsequent recovery of rangelands following better grazing practices has played an equally or more important role in large scale ecohydrological changes on these landscapes.

In South Texas, Basant et al. (2020) found that the expansion of woody plants in combination with the relaxation of grazing pressure resulted in dramatically lower surface runoff to lowland drainage ways, which likely contributes to lower streamflows at larger scales. Other studies found that reducing woody plant cover results in some increased deep drainage but in very moderate amounts (Weltz and Blackburn 1995; Moore et al. 2012).

In the Rolling Plains, a primary example of ecohydrological changes following woody plant encroachment and reducing grazing pressure comes from the North Concho River. The river flows near the boundary between the Edwards Plateau and the Rolling Plains ecoregions, with most of the river basin lying within the Rolling Plains. The average rainfall is 480 mm/year, and the aridity index is 0.2-0.3. Since around 1960, mean annual streamflows have been 70% lower than in the first half of the 20th century, a change that coincided with a dramatic expansion of woody plants, particularly honey mesquite. Water planners attributed the streamflow decline to increasing water use by expanding mesquite and, with the goal of restoring streamflows, they implemented a large-scale brush removal program in the North Concho watershed. Between 2000 and 2005, more than one-third of the 3100 km^2 watershed was cleared of mesquite. However, as reported in Wilcox et al. (2010), these substantial measures did not result in any perceptible increase in streamflow.

Wilcox et al. (2008a) conducted a detailed analysis of streamflow and precipitation records since 1915 in the North Concho. They found that streamflows make up a small portion of the water budget and that most streamflow is generated from large rainfall events. In other words, most of the streamflow results from infiltration-excess overland flow. They also found that flood flows were smaller and less frequent after 1960, even though average precipitation totals had not changed. These findings make sense considering the extensive vegetation changes that took place over the preceding 100 years. Beginning around 1880 and lasting until around 1960, rangelands in the Rolling Plains were extremely heavily grazed but, when livestock numbers declined precipitously, both herbaceous and woody plant cover increased dramatically (Wilcox et al. 2012). Contrary to expectations, the increase in tree cover resulted in higher soil infiltrability, a finding that was consistent with Wood et al. (1978) who found that in previously heavily grazed rangelands in the Rolling Plains, infiltration rates were twice as high under mesquite canopies than in the intercanopy areas. Several studies have found that mesquite expansion can increase evapotranspiration by a few millimeters a year (Carlson et al. 1990; Saleh et al. 2009) but in systems where most streamflow is generated as infiltration-excess overland flow, with only a small percentage coming from deep drainage, changes in evapotranspiration have little bearing on either groundwater recharge or streamflows (Wilcox et al. 2010).

Edwards Plateau: The Edwards Plateau straddles a considerable precipitation gradient increasing from 400 mm/year in the west to 900 mm/year in the east and the aridity index decreasing from 0.1 to 0.5 in the same direction. Despite its semiarid climate, the Edwards Plateau has numerous perennial springs, streams, and rivers. It is also the source area for the prolific and regionally important Edwards Aquifer, a major source of water for several urban areas and local agriculture. The explanation for this ecohydrological paradox is the underlying karst geology, which facilitates rapid, abundant groundwater recharge (Wilcox et al. 2007; Wilcox et al. 2008b).

Like other ecoregions in Texas, the Edwards Plateau has undergone radical vegetation change due to fire suppression, historic overgrazing, and subsequent woody plant expansion. Recognizing that such large-scale and dramatic changes in vegetation likely affect streamflows (Wilcox 2007), using data from four of the region's major rivers Wilcox and Huang (2010) analyzed long-term trends in streamflow. Using hydrograph separation techniques, they determined baseflow and stormflow volumes, the logic being that while both baseflow and stormflow may be affected by changes in vegetation, the mechanisms by which they are affected differ. Baseflows are affected by vegetation change that influences groundwater recharge, whereas stormflow is affected by surface changes that influence overland flow. Wilcox and Huang (2010) found that baseflows had effectively doubled in the wake of woody plant expansion and overall recovery from overgrazing. Given that vegetation (woody plants in particular) enhances soil infiltrability and that overgrazing degrades soil infiltrability, these results make sense. It is not clear to what extent changes in either vegetation cover or grazing pressure contributed to this baseflow response, because changes in vegetation cover were likely well underway before the period of hydrologic record. What is clear is that processes other than increased evapo-transpiration with increased woody plant cover were exerting a dominant influence on baseflow. Several studies have demonstrated that infiltrability under juniper trees is much higher than in adjacent interspaces (Wilcox et al. 2008b; Leite et al. 2020) and that overgrazing can result in reduced infiltrability (Centeri 2022). In this case, even though the higher infiltrability has decreased lateral connectivity, it has substantially increased vertical connectivity because of the karst substrate's high permeability. Increased rooting depth and transpiration capacity from woody plants may exert less influence on the hydrologic budget than infiltrability or other factors. In response to land use and land cover changes, both groundwater recharge and baseflows in the streams and rivers have risen significantly.

With respect to the WQPL, the key question is: *can removal of woody plants further increase groundwater recharge*? Based on our current understanding of rangeland ecohydrology it is reasonable to assume that groundwater recharge can be further increased with woody plant removal and the maintenance of high-quality grasslands. Changes in the water budgets in response to brush management in rangelands can be modest relative to total precipitation; however, reductions of less than 10% of evapotranspiration can equate to much larger gains as a percentage of groundwater recharge. As mentioned above, in the Post Oak savanna ecoregion, brush management increased deep drainage by a factor of 127, and in the eastern Edwards Plateau ecoregion, a decrease of 8% of evapotranspiration is equivalent to a 40% increase in groundwater recharge (Banta and Slattery 2011). The rationale is that (1) rainfall and aridity index at the far eastern Edwards Plateau are similar to the Cross Timbers and the Post Oak Savanna ecoregions where research showed that woody plants substantially increase evapotranspiration and thus lead to lower groundwater recharge and/or streamflow; (2) soils retain the high soil infiltrability up to a decade after woody plant removal, and (3) grazing pressure is extremely light in the WQPL fostering lush mid and tall grasses that ensure high soil infiltrability. In addition, evapotranspiration is likely less for grasses than for dense woody plant cover (Dugas et al. 1998; Heilman et al. 2009; Banta and Slattery 2011). Based on these finding, the WQPL are good candidates for brush management for the purpose of increasing water yield. The approach for conducting a benefit cost analysis of such brush management is detailed in Appendix 4.

In conclusion, overall recommendations to guide the management of the WQPL are:

1. Do not allow development or urbanization of the lands.
2. Fully mitigate the deleterious effects of any improvements (e.g., roads, trails, etc.).
3. Manage the lands to best protect and improve water quality and quantity through restoration of prairie, savanna, and riparian vegetative communities.

For item number 3 above, recommendations to guide and prioritize WQPL site selection for brush removal as part of prairie and savanna restoration include:

1. Where most existing woody cover is encroaching, where terrain is relatively flat (less than 10% slope), and where there is no occupied Golden-cheeked warbler habitat. In such areas, setbacks from surface water should be provided for chemical treatments and mechanical cutting in floodplains should minimize soil disturbance and woody debris by removing from waterways.
2. In upland areas, prioritize shallower soils.
3. Avoid soil disturbance near sensitive sites such as riparian corridors and internal drainage basins associated with karst features.
4. Evaluate experimental treatments on a small scale to ensure desired results before widespread implementation.
5. Minimize soil disturbance by mechanical equipment and seeding application and ensure that soil crusts are protected from erosion by slash or light mulch cover.
6. Gradually reduce woody cover in savanna grassland areas until below 15%.
7. Ensure long-term maintenance of grassland vigor and brush reduction.
8. Monitor the results.

3.3 Management Goals and Objectives

3.3.1 Goals

1. Address issues in land management planning and implementation that directly affect water quality and quantity. These include, in order of priority:
   - Vegetation management, including thinning of trees and brush, to maintain surface infiltration of high-quality water.
   - Balance land use and management options with water quality/quantity protection.
   - Reduce runoff contamination from point and non-point sources associated with on- and off-site activities.
   - Protect or enhance riparian areas and riparian buffer strips to enhance water quality.
   - Enhance the capture of precipitation and its recharge into the aquifer.
   - Protect and enhance biodiversity for the benefit of habitat and watershed function.
   - Work with the city, stakeholders, and other partners to acquire adequate budgets for successful project implementation.

2. Address issues within the broader context of sound natural resource management and in the face of the global biodiversity and climate change crises (see Appendix 5). Specifically focus on issues that relate to ecosystem restoration for the purpose of protecting or enhancing the ecosystem services beyond water quality and water quantity. Ecosystem services are goods and services that directly and indirectly enhance human wellbeing and that are produced by ecosystem processes involving the interaction of living elements, such as vegetation and soil organisms, and non-living elements, such as bedrock, water, and air. Potential ecosystem services derived from the WQPL include, but are not limited to, surface water filtration, wildlife habitat provision, pollination, and maintenance of high native biodiversity.

3. Address issues that do not directly affect water provisioning or other ecosystem services but are critical to project success. These include, in order of priority:
    - Manage an appropriate public participation process that emphasizes equity among all social groups (See Appendix 6). This process gives stakeholders ownership of the project to help fund actions and build public support, address public access issues, and help build relationships between stakeholders and the City.
    - Address infrastructure needs to provide for security, staff access, and public access.
    - Provide for public education and information about the WQPL, its management, and activities occurring there.
    - Monitor land treatment, management results, and public activities on the land.

4. Address issues which are not critical to water provision, other ecosystem services, or the overall success of the project but that will enhance the overall quality of the project. These include, in order of priority:
    - Seek funding to support future acquisition of land.
    - Support natural resources-related education and information activities.
    - Maintain the rural character of these lands and preserve cultural and historic resources associated with them.
    - Assist with research to develop or improve watershed best management practices for central Texas.

3.3.2 Objectives

Management activities will be structured to restore or ecologically move the systems toward, or maintain them at, a target vegetative community composition and structure. The target communities were chosen based on which community would best serve the stated goals, the historic plant communities provided by the NRCS ecological site descriptions, the current condition of the site, and the practicality of moving toward a given community. An overview of general treatment regimens can be found in Figures 24-34.

3.3.2.1 Riparian Areas

Target communities in riparian areas are either properly functioning riparian woodlands with an herbaceous layer beneath (Nelle 2009), or more open canopy savanna structure with continuous grass cover. In both cases, riparian herbaceous cover is composed primarily of species with NRCS stability ratings between 6 and 9. Stability ratings range from 1 to 10, with 1 approximating the bare ground and 10 representing anchored rock. Historically, many riparian areas along perennial and frequently flowing intermittent streams on the Edwards Plateau were of the gallery forest community type. Continuous herbaceous coverage by species with high stability ratings best supports the goal of enhanced water quality along stream channels by enhancing bank stability, removing nutrients and other pollutants such as sediments, and helping to aggrade stream channels and slow water velocities. Riparian areas over the recharge zone have proven challenging to manage for high woody cover and more frequently resemble nearby upland communities, while contributing zone lands support gallery forests comparatively easily.

3.3.2.2 Upland Areas

The target community for most upland areas is a tall or midgrass savanna with woody cover below 15%, where possible. Savanna is defined as a grassland matrix with scattered trees, and it is the historic climax plant community for much of the WQPL. Improper grazing practices and fire suppression have allowed woody species, particularly Ashe juniper, to increase dramatically in cover and density. Savanna or prairie restoration supports the goals of enhanced water quality and quantity, as discussed in Section 1.3.

3.3.2.3 Endangered Species

Recommendations will adhere to current state and national requirements for land management activities in and around endangered species habitat. Management activities in and around endangered species habitat can be modified to provide greater protection to endangered species where conditions warrant.

3.3.2.4 Invasive Plant Species

Invasive species can reduce biodiversity and, in some cases, work against the WQPL's aquifer recharge goal. Invasive species that counteract these goals should be managed in an appropriate manner according to the IPM plan in place for the WQPL.

3.3.2.5 Oak Wilt

Oak wilt is a fungal disease infecting primarily red oaks such as Spanish oak (*Quercus falcata*), Texas red oak (*Quercus buckleyi*), Shumard oak (*Quercus shumardii*), blackjack oak (*Quercus marilandica*) and live oaks. This disease spreads via the root system or insect vectors. The most common control measure involves trenching around affected trees to sever root grafts between trees and thereby control the spread of the fungus. Additionally, affected individual trees may be treated by periodic injection of a fungicide. Due its high cost, this treatment is typically reserved for very high value trees. In general, aggressive control of oak wilt within the WQPL is not recommended; saving oak trees lies outside the primary goal of protecting water quality and quantity. Moreover, trenching disrupts the soil, leads to reduced water quality, provides a pathway for invasive species establishment, and is very expensive. Finally, 10% of oaks will typically survive exposure to oak wilt and those that do provide a seed source of fungus resistant progeny (Johnk et al. 2006).

Trees found to have oak wilt can be evaluated on a case-by-case basis. Situations in which treatment may be warranted include: (1) Trees found in and around Golden-cheeked warbler habitat, because the Texas red oak and the insects that feed on it are an important food source for the birds (however, endangered species habitat enhancement is not a primary goal of the WQPL); and (2) near property boundaries where it is possible for oak wilt to spread beyond the boundaries of the WQPL. General precautions should be followed to avoid spreading oak wilt, including avoiding wounding oaks between February and June when fungal mats are most likely to form, painting any cuts in oak trees with a tree coating material, disinfecting tools used on infected trees, and avoiding storage of the wood of felled infected trees near healthy trees. Since the fungus is heat sensitive, there is no danger of spreading the fungus via prescribed burning.

3.3.2.6 Woodland Health

Though the general vegetative goal for upland areas is savanna grassland, some areas are not appropriate for savanna restoration. This can be due to factors such as the presence of Golden-cheeked warbler habitat, cost, rough terrain that would make mechanical brush treatment impractical, and/or some characteristic of the property (small size, location near developments) that makes maintenance with prescribed fire impractical or inadvisable. The management objective for these areas should be increased woodland health. The past suppression of natural disturbances such as fire has allowed many of the woodlands found on the WQPL to develop into juniper monocultures, often with even-aged stands and little to no herbaceous layer. Additionally, recruitment of young hardwoods is often prevented by excess browsing pressure from species such as white-tailed deer. In this state, the woodland is less resilient to disturbance and provides poor habitat for species such as the Golden-cheeked warbler, which requires both mature juniper for nesting material and broadleaved trees and shrubs to harbor the invertebrates that warblers feed on.

Increased woodland health can be encouraged through restoration of natural processes, such as fire, or activities that mimic natural disturbances, such as disease and insect kill, which create canopy openings that vary in size, shape, and location. This encourages the woodland to move toward a state with mixed age stands, increased species diversity, and a diverse herbaceous layer. To this end, Ashe juniper can be selectively thinned to allow recruitment of other species. Thinning should be done in small patches to mimic natural canopy openings. Following thinning, the opening can be seeded with appropriate hardwood and herbaceous species. Juniper seedlings emerging in the area will need to be mechanically controlled. It may be necessary to control white-tailed deer and perhaps to fence or mechanically protect young hardwoods. Tree architecture may also be modified to “limb up” trees simulating the effect of low intensity ground fires which kill lower branches of many woody species and promote herbaceous growth. Prescribed fire may also be a tool on some sites either as a follow up to mechanical thinning, or in some cases in place of mechanical thinning where a continuous herbaceous layer could carry a surface fire without risk of significant impacts to the canopy. Smaller woodlands within larger savanna burn units may be allowed to burn through if there is a low likelihood of extensive crown fires or widespread torching. Fire in Golden-cheeked warbler habitat may proceed if not otherwise prohibited by the U.S. Fish and Wildlife Service (USFWS). As stated previously, land managers should consult with USFWS when planning land management activities within occupied Golden-cheeked warbler habitat that could impact canopy cover.

3.3.2.7 Prescribed Burning and Wildfire Risk

Elevated fuel loads together with projected hotter, drier climatic conditions will likely lead to more frequent erratic wildfires in the western USA (Luo et al. 2013). Recognition that changing climate and decades of fuel accumulation are increasing wildfire risks has led to calls for the greater use of prescribed fire. However, this shift in fire management emphasis is failing to take effect due to entrenched disincentives to work with fire because of liability concerns and little tolerance for management errors (North et al. 2015). While the debate about fire management reforms has focused mostly on federal lands, this issue is equally applicable to private and city-owned rangelands that can be the source of and conduit for wildfire (Fischer and Charnley 2012). This includes the Edwards Plateau, which consists primarily of private land, and which has experienced significant woody plant expansion.

While there is an urgent need to reduce wildfire risk using prescribed fire, this tool is substantially underutilized on both private and municipal lands (Twidwell et al. 2013). Reasons for this deficiency include inadequate knowledge about safe fire application, lack of labor and equipment on burn days, erroneous perceptions of high liability risk (due to public conflation of wild and prescribed fire), and burn bans during times when prescribed fire would most effectively reduce encroaching woody plants and accumulated fuel loads (enactment by risk-averse county commissioners who are primarily advised by emergency personnel tasked with extinguishing fires) (Kreuter et al. 2008; Toledo et al. 2014; Wonkka et al. 2015; Kreuter et al. 2019; Stroman et al. 2020; Weir et al. 2019; Hinojosa et al. 2020; Hoffman et al. 2021; McDaniel et al. 2021; Clark et al. 2022). One initiative that has substantially overcome barriers to the broader use of prescribed fire is the establishment of prescribed burning associations (PBAs) that provide safe fire training, labor and equipment on burn days, and, in some cases, escaped fire insurance for their members (Twidwell et al. 2013; Toledo et al. 2014). The WQPL might benefit from joining a PBA. This would increase the amount of labor and equipment available on burn days and, therefore, potentially increase the area burned annually, reducing fuel loads.

The WQPL program recognizes the role it plays in building both community and landscape wildfire resilience by reducing the risk and severity of wildfires on lands under its care. To address this, the WQPL proactively installs firebreaks in areas that border neighborhoods, both by mowing grassy areas during the growing season and through tree canopy shaded fuel breaks in woodier areas. The WQPL program also conducts prescribed fires on savanna grasslands to reduce grass and thatch fuel loads and therefore the risk of wildfire in the short term. In the long-term, the regular implementation of prescribed fire reduces the severity of wildfires when they do occur by consuming biomass and brush which can contribute significantly to fire intensity.

Beyond these active management efforts, the WQPL uses Wildfire Prevention Plans to reduce the likelihood of unintended ignitions. All projects conducted by staff, contractors, or volunteers require completion of such a plan, which describes the nature of work to be conducted and an emergency plan in the event of an ignition. They also require a spotter during high fire danger. (For template, see Appendix 7).

The WQPL is also active in facilitating line access for electric utility providers such as Pedernales Electric Cooperative and Austin Energy. Regular powerline maintenance reduces the likelihood of wildfire ignitions caused by contact of vegetation with overhead lines or equipment malfunction. While the WQPL is not responsible for the maintenance of lines traversing its land, WQPL staff do actively facilitate access to electric lines for inspection and maintenance and report issues, such as vegetation encroachment, to the relevant provider to ensure potential issues can addressed early.

Finally, the Wildland Conservation Division (WCD) has generated contingency planning documents for the use of emergency responders. These plans include detailed mapping that describes projected fire behavior, values at risk, access, and roads. The contingency planning documents would facilitate rapid response and increased situational awareness for firefighting resources responding to ignitions on WCD lands.

Through use of wildfire fuel mitigation activities, active ignition prevention programs and coordination, and contingency planning for wildfires which may occur on managed lands, the WQPL program fulfills its role as a manager and steward of the wildlands under its care while also doing its part to reduce both ignition potential and fire severity in the event of a wildfire emergency.

3.4 Recent Management History (2000-2020)

Figures 35-41 show treatment frequencies on the WQPL, expressed as the treatment return interval, which is the average number of years between thinning or fire treatments. Most grassland savannas on the WQPL have had a treatment return interval of 3-6 years. Appendix 8 shows the treatment effects on woody plant cover.

Most savannas on the WQPL were treated with at least one mechanical juniper cutting treatment soon after acquisition by the City of Austin. Some were then also treated with multiple prescribed burns, and some may have also received a secondary mechanical treatment targeting resprouting shrub species, or a subsequent juniper cutting treatment to target a larger size class than the initial treatment. Areas that have received at least three mechanical thinning or prescribed burn treatments are generally grass-dominated and have intermediate woody plant canopy cover of between 20% and 40%. Most of the Little Bear Creek and Onion Creek Management Units fit this description. Woody encroachment rates typically range from 1.5-2.5% per year on these sites (Yang and Crews 2020)(see Appendix 8). While Ashe juniper cover is often relatively low on most of these treated sites, more disturbance-tolerant resprouting shrubs, such as mountain laurel and Flameleaf sumac (*Rhus lanceolata*) tend to become the dominant shrubs, and cedar elm (*Ulmus crassifolia*) may replace Ashe juniper as the codominant tree along with live oak. Although Ashe juniper suppresses herbaceous growth and ground-level fine fuels more effectively than other species, any woody overstory reduces surface light levels and concomitant herbaceous biomass. By reducing fine fuel loads, temperatures, and windspeeds and increasing humidity, woody cover induces feedbacks that reduce surface fire frequency and woody plant suppression efficacy. While other woody plants may coexist with greater amounts of herbaceous biomass in small patches, woody cover greater than about 40% has been observed to inhibit or preclude surface fire spread in other savannas (Staver et al. 2011a). Savannas can generally be maintained at current canopy cover levels by applying two prescribed burns per decade, without additional mechanical thinning treatments, if each fire reduces the canopy cover by around 5-10%, which is a typical response according to WQPL transect data (Appendix 8). The potential benefits of treatments to reduce canopy cover can include increased water yield, reduced maximum potential wildfire severity, and longer treatment return intervals.

Some savannas on the WQPL have less than 15% canopy cover and, while woody plant encroachment rates on such sites is not well documented, they are likely lower than on intermediate canopy cover sites due to the logistic growth patterns in the eastern Edwards Plateau (González 2010; Yang and Crews 2020). Such areas may be burned once per decade or less to maintain current canopy cover levels, while burning once or more per decade may benefit herbaceous composition. Water yield is probably high and maximum potential fire severity is probably low on these sites, due to limited rooting depth, non-summer transpiration, and limited fuel loading. Some high elevation sites on the Onion Creek and Slaughter Creek management units fit this description well.

Some sites on the WQPL received an initial juniper cutting treatment, but no subsequent management interventions in the following years. In such cases, the initial reduction in woody cover reversed through woody recovery. This kind of site may support reasonable herbaceous composition with little King Ranch Bluestem, which requires full sun, and where juniper saplings or more disturbance tolerant woody species have replaced previously cut junipers. The southernmost sites on the Slaughter Creek management unit and the northernmost sites on the Bear Creek management unit fit this description well.

Woodlands on the WQPL have generally not been subjected to management intervention, other than exotic species removal. These occur in three scenarios: sites that are not suitable for canopy reduction due to the existence of Golden-cheeked warblers, sites where herbaceous cover and diversity are low and woody cover is nearly complete, and sites where surrounding land use effectively precludes the implementation of prescribed fire. These areas may benefit from brush management treatments to improve woodland health, oak recruitment, pre-adaptation climate resilience, water quality, and/or fuel reduction. These objectives are secondary compared with brush management and maintenance treatments in savanna habitats. Management resources for savanna and woodland habitats on the WQPL draw from the same pool. The benefits and practicality of prescribed fire in savannas appears to be better than in woodlands, which is why woodlands have remained largely unmanaged, except for fencing, patches that occur in a savanna-dominated burn block, and fuel break/access corridor treatments along property boundaries.

Land management implementation on the WQPL has consistently fallen below target acreage levels. Specifically, prescribed fire implementation has been inadequate due to one or more of the following challenges:

- Lack of fire readiness (e.g., fire line preparation, equipment failure, labor and burn boss availability).
- Unsuitable weather (e.g., extended drought, unfavorable wind, humidity or air temperature, and poor forecast accuracy).
- Regulatory restrictions established by local and county jurisdictions.
- Adverse public perception based on incomplete information about prescribed fire.

In the period from 2002 to 2021, 10,210 acres were burned on the WQPL, averaging only 511 acres per year. However, in 2007 the Wildland Conservation Division first hired a burn boss. Between this year and 2017, apart from the record drought year of 2011, 8,709 acres (averaging 871 acres per year) were burned.

The total acreage of savanna habitats located within established burn units on large, contiguous tracts in the Onion Creek and Bear Creek watersheds is 7,078 acres. Allocating the 511 acres annual average burn area only to those 7,078 acres would equate to a fire return interval of 13 years, whereas if the 871 acres per year achieved between 2007 and 2017 (excluding 2011) targeted only these 7,078 acres, the fire return interval would equate to 8 years. Using a woody encroachment rate of 2% per year, the preceding fire return intervals would facilitate woody encroachment greater than 25% between burns based on average acres burned per year over the entire program history and 15% between burns from 2007 and 2017 (excluding 2011). Based on unpublished transect data from the WQPL (see Appendix 8), canopy reductions from prescribed burns are approximately 5%. According to a global meta-analysis including many savanna ecosystems with similar climates to the Austin area, woody plant abundance declines with fire return intervals of 1-3 years for about six decades (Pellegrini et al. 2021). To maintain a 3-year fire return interval on the 7,078 acres in the WQPL that are most conducive to prescribed burning would require an average annual burn area of 2,360 acres, which is almost 3 times as much as that achieved during a decade of prime performance years for the WQPL fire program. Based on twenty years of land management experience on the WQPL, we can conclude that substantial additional prescribed fire resources are necessary to optimally protect long-term groundwater supply for the Barton Springs segment of the Edwards Aquifer and reduce the maximum potential intensity and severity of wildfire on the City-owned WQPL.

3.5 Public Access

Throughout the development of the original land management plan for the WQPL, as well as the 2011 and 2022 revised plans, both the City staff and the general public expected that there would be some public access on the WQPL. The initial management plan identified some areas, depending on location and tract sensitivity, where trail access was appropriate for various user groups, if funds for construction and maintenance of these trails be raised outside of Austin Water. Trails on the Bull Creek and Slaughter Creek Management Units that were identified in the 2001 plan have been constructed and are now open to the public.

This section outlines the general principles that guided initial discussions of public access, a description of the public participation in 2001 in the decision-making process regarding public access on WQPL, a description of the anticipated impacts that could occur because of the public access activities, and a discussion of some of the mitigation measures to decrease or eliminate adverse impacts. Additional discussions for trails in other management units of the WQPL are currently underway.

3.5.1 Guiding Principles for Public Access

In keeping with the bond language and conservation easement agreements as well as the WQPL goals described in Section 3.3, the following guiding principles have been used in considering public access:

- Some level of public access will occur on WQPL.
- Any negative impacts of access on the WQPL properties should be fully mitigated so there is no net loss to water quality, water quantity, or other ecosystem service.
- The WQPL cannot become parkland in name or intent. They serve primarily to enhance the City of Austin's water supply in perpetuity. All access occurring on the WQPL must support this mission.
- Austin Water receives funding for maintaining the WQPL from its customers; therefore, providing funding for more than limited education-related access is beyond its mandate. Other public access must be based external resources for developing, maintaining, and mitigating any other activities.
- Only limited City staff time will be used for development, maintenance, and mitigation activities relating to public access on WQPL.
- Public access on any conservation easement is at the discretion of the landowner.

3.5.2 Public Stakeholder Process

Based on the guiding principles above, a multi-tiered approach was used to assess the suitability of various types of public access activities and to develop a public stakeholder support base for selecting, implementing, and managing public access on WQPL. In the initial land management proposal, the LMPG identified 46 groups that should be contacted concerning public WQPL access, and this increased to over 100 groups by December 1999. A survey was conducted to assess their desires for public access on WQPL. Fifty-five survey responses were received from 42 stakeholder organizations and 13 individuals without associations. The leading interests and concerns expressed by the respondents were: Preservation of habitat; public access and use; recreational hiking and cycling trails; horseback riding; and public education. The leading proposed uses were: (1) Recreational hiking and cycling trails, (2) other passive uses, and (3) horseback riding. Additionally, the leading "hopes, wishes or vision" were the preservation of the land and its natural resources balanced with passive uses such as trails, horseback riding, and education. Seventy percent of the respondents stated that they would be willing to make significant contributions of volunteer time and, in some cases, the ongoing management and operation of the WQPL. Additionally, over 90% of the respondents were interested in participating in a public involvement process to determine the best use of the city-owned WQPL.

Following this survey, the LMPG invited all interested parties to participate in a facilitated Stakeholder Steering Committee to help determine what public access would be allowed, where it would be allowed, and how the public access facilities would be funded and maintained. The Committee's recommendations then went to the Water and Wastewater Commission for approval and then to City Council for final approval. The facilitated stakeholder meetings began in September 2000 and continued over an 18-month period. It was the intention of City staff that this stakeholder involvement would continue, and the Committee continues to meet as needed. Initial recommendations from this group were developed in April 2001. The group has emphasized that educational activities should occur on all WQPL properties and that several multi-use trails should be constructed and maintained on tracts where trails are expected to have the least adverse impact and have the greatest potential for mitigation.

3.5.3 Anticipated Impacts from Suggested Uses

3.5.3.1 General

Recreational use, such as hiking, biking, horseback riding, camping, picnicking, and hunting, can impact physical, biological, and cultural resources of natural areas (Cole 1990, Sun and Walsh 1998). Primary impacts include:

- Compaction and erosion that lead to physically and biologically altered soils.
- Changes, losses, or additions to revegetation composition and abundance.
- Altered animal behavior due to habitat change or human presence.
- Diminished "wilderness" perception due to negative effects of human activities on pristine aesthetic quality of the environment (Roggenbuck et al. 1993).
- Interference with, or prevention of, land management activities that are necessary to preserve and enhance water quality and quantity values derived from these lands.

Secondary impacts include gully erosion, sedimentation of streams, habitat fragmentation, and invasive plant species introduction. Additionally, these activities may require the provision of road and parking facilities with impervious cover. The impacts of such infrastructure can be reduced by connecting to existing trails or parking facilities but otherwise must be mitigated by partnering agencies.

3.5.3.2 Soils

Changes in the natural soil structure that reduce infiltration (e.g., compaction, imposition of impervious cover, etc.) increase surface runoff and erosion and are detrimental to water quality and quantity. Proposed recreational uses should be evaluated for their effect on soil structure and function. Different types of traffic (e.g., hikers, bicyclists, horseback riders) can have different effects on the soils of intensively utilized recreational sites (Pickering et al. 2010; Salesa and Cerda 2020; Evju et al. 2021). To avoid adverse impact on the recreational area in general, the variables of soil type and depth should be considered in relation to precipitation, traffic density, traffic type, trail design, and topographic slope (see Tinsley and Fish 1985, Selesa and Cerda 2020 for review).

Soil erosion may be the greatest potential problem from poorly constructed and managed trails. In most terrestrial systems, erosion occurs naturally but accelerated erosion may occur where this process is enhanced by human activities (Borrelli et al. 2017; Poesen 2018; Borrelli et al. 2020; Salesa and Cerda 2020). Trail traffic can increase erosion due to soil loosening (particle detachment) and compaction (increasing run-off), as well as concentrating water flow into channels, thereby increasing down-trail sediment transport (Salesa and Cerda 2020; Zemke 2016). Wet soil conditions exacerbate these processes. The nature of the surface itself may influence erosion potential. More massive, weakly structured soils with low infiltration rates may be more susceptible to erosion than well aggregated soils (Eckert et al. 1979). By contrast, shallow-soiled, 'rocky'-surfaced trails tend to be more erosion and compaction resistant (Bryan 1977, Eckert et al. 1979), however vegetation growing in these soils is less able to recover from damage than plants growing under more favorable conditions (Liddle 1975, Leung and Marion 2000).

Soils with higher erodibility are more susceptible to sheet and rill erosion by water. One strategy to minimize erosion is to avoid public access on areas with high erodibility soils. However, those soils tend to be relatively thin and provide a less hospitable growing environment for plants than deeper soils; plants growing in them are less able to recover from damage than plants growing under more favorable conditions. This tradeoff needs to be considered in decisions about public access. A second way to minimize erosive effects is to ensure that infrastructure for public access is developed when water run-off potential is at its lowest and that public access is restricted when the site is most erodible. Due to rainfall patterns in the Austin area, soils are most prone to erosion from November through March, and least prone to erosion in June through August. To reduce erosion, activities such as trail construction, should occur from late April through early October, with the least erosive times typically occurring in July and August (Renard et al. 2001).

Two other factors to consider in reducing activity-related is to minimize the slope and downhill length in which the activity is to occur. Dispersed-use activities should occur on generally flat topography, and concentrated-use activities should follow contour lines. Trails should utilize switchbacks, steps, terraces, and other means to reduce the downhill length where water can run.

In summary, the relatively shallow, well drained, and sometimes rocky soils of the Edwards Plateau may allow for trails without undue peripheral erosion. With adequate design and maintenance, the development of erosive features can be minimized. However, a trade off exists between soil erodibility and the resilience of plants growing in the soil. The potential impacts to vegetation must be considered along with direct impacts to soil because the state of the vegetation strongly influences soil characteristics, the overall erosion from an area, and water quality and quantity. More sensitive areas, such as internal drainage basins associated with karst features, riparian areas, or wetlands, will require additional care to protect soils from erosion both during and after construction, or they should be excluded from recreational use altogether. Even with precautions, it is likely that the trail bed will suffer considerable degradation unless it is surfaced or infrequently used.

3.5.3.3 Vegetation

Trampling of vegetation is frequently the primary effect of recreational use of natural areas (Cole 1990, Marion and Cole 1996; Pescott and Stewart 2014). Trampling impacts vary across landscapes and depend on vegetation type and recovery time and may even enhance growth of some species (Pescott and Stewart 2014). Long term trampling may result in the removal of trample-sensitive species within the disturbed area, and it may encourage those species that respond positively to disturbance to increase, including invasive and/or exotic species (Cole 1990; Roovers et al. 2004).

The affected zone around trails may be narrow, but it may be extensive around more dispersed recreation activities such as camping or trailheads (Dale and Weaver 1974; Roovers et al. 2004). In addition, impacts can extend far beyond the primary impact zone as sediment moves across the landscape or if introduced exotic species alter the plant dynamics (Leung and Marion 2000). The increase in abundance of alien species (invasive or otherwise) is a potentially serious consequence of increased disturbance around recreation areas. The abundance of alien species increases as exotic seed is imported by traffic and native plant communities are rendered more vulnerable to invasion by the disruption of ground cover and weakening of individual plants. This is particularly common in areas where there is both high traffic and long visitor residence time.

Recreational activity can also pose a wildfire risk (Sun and Walsh 1998). People recreating on WQPL may accidentally ignite wildfires that compromise public safety and ecosystem management goals. Escaped campfires, smoldering cigarettes, and hot automobile engines are common causes of human-caused wildfires. Wildfire risk varies throughout the year, and typically corresponds to late winter/early spring and mid/late summer, when dead fine fuels are extremely dry and vegetation moisture is low due to drought. Texas A&M Forest Service provides fire danger and fuels forecasting (https://twc.tamu.edu/tfd), which may be used to determine when recreational activities require additional precautions to avoid wildfire. Because native vegetation of central Texas is always fire prone, management of WQPL to reduce fuel loads via prescribed fire will be essential to limit wildfire risk from recreational activities. This will likely require prioritizing commonly used recreational areas for prescribed fire or other fuels reduction treatments, such as mowing or grazing.

The overall vegetational effect of trail traffic is that although the species composition within the feature itself may be dramatically altered, this response decreases with distance from the feature, and impacts will be most severe near the trailhead (Bright 1986). Taking precautions beyond careful trail design to prevent erosion, such as surfacing the trail, should be considered in high impact areas such as trailheads and in areas of high sensitivity, such as riparian areas or areas with a high concentration of karst features.

3.5.3.4 Fauna

Immediate short-term impact on wildlife, such as temporary flight of birds or land animals, can be expected due to the presence of people or horses on trails (Burger and Gochfeld 1998). Long-term effects from habitat interference by trail construction may be significant, particularly on micro-scale organisms, and cannot be mitigated. General traffic in the surrounding area, the collection of firewood, the presence of trash, water supplies, etc., can significantly modify habitat, expelling some species while attracting others (Cole 1990). Human presence can also directly affect many animals by inducing stress in individual animals and alter their behavior (Cole 1990). Where high densities of visitors prevail over longer time periods, most animal species will experience population decline. There is also the chance that a few species may be attracted to these areas due to available water sources, litter, light sources, etc. (see Cole, 1990 for review).

3.5.3.5 Interference with Land Management

Land management activities on the WQPL are designed to ensure that the goals outlined in Section 3.3 are met; disruption of these activities will impede progress toward program goals. Public access can interfere with land management by directly impacting activities or by diverting resources away from land management.

Austin Water has no mandate to provide public access within the WQPL beyond a limited allowance for the purpose of public education, and the majority of the WQPL's limited funds are intended to serve program goals. If significant public access is to proceed, most funds for construction, operations, and mitigation must be raised outside of Austin Water. However, public access will require some management by WQPL staff even if a separate trail management and funding structure exists. Trail users periodically leave the trail, damage property, etc. and these situations must be dealt with by WQPL staff. Additionally, the presence of trails increases the cost and complexity of management activities near the trail. For example, the trail must be closed in advance of some activities such as prescribed fire or hog population control. In such instances, staff need to devote resources to closing and patrolling the trail after closure to ensure there is no unauthorized access. It is anticipated that some program funds will need to be used for the mitigation of trail impacts.

3.5.3.6 Trail Maintenance

Trails must be managed by partnering agencies and volunteers under agreements arranged in coordination with the Stakeholder Steering Committee. WQPL staff must inspect trails annually to ensure compliance with agreements, with an emphasis on erosion issues, off-trail impacts, and illicit use including trail expansion, dog walking, littering, and dumping. A map project within the ESRI Field Collector app has proven useful in documenting recreational impacts on natural resources. This allows staff to efficiently document and archive trail impacts using dropdown menus and geolocation data, and to generate maps to share with partners. It is important for trail stewards to check trails after rain events, to close them to visitors if necessary, and not open them again they have inspected field conditions and confirmed that the trail surface has dried out sufficiently to no longer be vulnerable to erosion or compaction from recreational access during saturated conditions. Opening, closing, and monitoring trail conditions relies on intensive and regular volunteer effort. When unauthorized use becomes a regular pattern or increasing trend, it may become necessary to temporarily close the trail to all users, which should encourage peer enforcement. This strategy may also become necessary if managing partners are unable to comply with agreements established by the Stakeholder Steering Committee, especially if trail condition is degrading and erosion or other impacts are not being adequately mitigated.

3.5.3.7 Mitigation Measures

Adequate design of recreational features, such as trails, is essential to minimize soil and vegetation degradation. Main principles for trail construction include following contours as much as possible, out-sloping the trail bed, avoiding sharp turns, preventing spontaneous 'shortcuts', and arranging frequency of cross drains (water bars) and dips according to soil type and grade (USDA 1985, Felton 2004). Recommendations specific to soil type and grade can be found in USDA (1985, 1999) and Birkby (1996). Additionally, trails should maintain a buffer of at least 100 feet from creeks and avoid riparian zones where this buffer is inadequate except at constructed creek crossings to avoid streamside damage. Whenever possible, trails should be kept far enough away from creeks and other water bodies that users cannot see them to discourage them from creating social trails to the water. Trail construction could also be used as a restoration tool by improving topographic structure in areas currently experiencing erosion problems. If roadway or parking facilities are to be developed, they must be carefully sited and designed. Pipe and gutter systems should be avoided and alternative paving systems, such as grid pavers or pervious pavement, should be considered to reduce impervious cover. Impervious infrastructure should be designed such that runoff is treated and infiltrated to mimic the pre-development hydrology by using bioretention filter devices, and flow conveyance via vegetated swales and natural channels.

Access should be limited or prohibited in some places, especially riparian areas, wetlands, or areas with extensive karst features or internal drainage basins linked to such features. Even in less sensitive areas, it will be appropriate to prohibit public access for some period after rainfall events until the soils are sufficiently dry. Additionally, certain plant communities may be considered particularly valuable or sensitive, and may be unsuitable for recreational development, especially in areas with very shallow soils and wetlands. Habitat for endangered or protected species, such as Golden-cheeked warbler and karst-dwelling invertebrates, will also require particular attention.

Generally, some impact from these collective activities is inevitable but justifiable if impacts can be properly mitigated and if access allows the public to be educated about the importance of healthy ecosystems to improved water quality and quantity. This knowledge can then be taken back to affect a much larger area than that of the public lands. Impacts that cannot be properly mitigated should be avoided.

The development of sports fields is not recommended because they are typically vegetated with invasive bermudagrass, and fertilization and irrigation are normally required to maintain a dense cover of turf grass. Additionally, more parking and restroom facilities would be needed, increasing deleterious access impacts. How to mitigate such impacts is unclear and, therefore, because the WQPL must be maintained to enhance water quality and quantity, the management team does not recommend developing playing fields.

During the design phase of any public access activity, it is imperative that GIS-based suitability analyses are conducted to ensure the most efficient design of trails and recreational areas. Additionally, once constructed, these must be adequately monitored to detect positive or negative trends.

Section 4
Future Management Recommendations

4 Future Management Recommendations

To guide prioritization for restoration, it is important to identify the places on the WQPL that are most like historical plant communities (Table 2) and thus require conservation focused management, as opposed to restoration treatments. Specifically, managers should map and prioritize prescribed fire in the few remaining old-growth grasslands (Veldman et al. 2015) that exist on the WQPL and that are among the few examples of the historical savanna plant communities of central Texas (Table 2; USDA-NRCS 2013; Novak et al. 2021). Likewise, managers will need to identify mature woodlands that should not be candidates for savanna restoration (Veldman 2016). In sum, conservation of existing high-quality habitat is far easier than restoration, and thus old-growth ecosystems—whether grasslands or woodlands—should be priorities for conservation (Buisson et al. 2022). For this reason, priority will be given to 1) preventing woody plant encroachment in existing prairies and oak savannas, 2) reducing canopy cover in grasslands undergoing recent woody encroachment, and 3) expanding savanna restoration areas over time.

Each of the WQPL management units has been subdivided into one or more of four treatment units based on land types described in Section 1.6 (Figures 24-34). Management recommendations are made based on the goals provided in Section 3.3 and the current ecological state of the treatment unit with a desire to prioritize management in those areas that will contribute most to the attainment of the WQPL goals. Management strategies will need to be adaptive to reflect changing site conditions, climate variation, and the projected long-term climatic changes. In addition, areas may exist within treatment units that require a different management approach than that applied more generally across the entire unit. Typically, this will occur within occupied endangered species habitat, riparian corridors, or in near particularly sensitive features such as springs, seeps, and recharge features.

4.1. Adaptive Management

4.1.1 Overview

This management plan is intended to provide land management guidance for the City of Austin's WQPL for the next 10 years. Because natural systems are dynamic and respond to many factors, including extreme weather such as drought and disturbances such as fire, management strategies should adapt to changing conditions (Roux et al. 2022). This approach is called adaptive ecosystem management (Conallin et al. 2018; Dirk et al. 2022). Such management focuses on four elements: *inventory* of the current conditions; *desired future conditions* and the strategic goals for attaining them; *planning and implementation of specific actions* for achieving the desired future conditions; and *monitoring of outcomes* to determine if actions are leading to desired future conditions. This process is iterated with adaptations being made if management outcomes are inconsistent with the desired future conditions or if the desired conditions change. For the WQPL, adaptive management is broadly defined as goal-oriented decision making in which management actions are informed by monitoring site conditions to maintain or enhance the functionality of ecosystems that provide the targeted ecosystem services. Additionally, research on ecosystem response to specific management tools, such as periodic prescribed fire, should be incorporated into the cyclical management and ecological effects monitoring actions.

Ecological monitoring data can be assessed by comparing conditions of a similar reference ecosystem or by comparing conditions of the management site to model outputs derived using input data from various sources to re-construct conditions under which desired ecosystem services are optimized. The latter approach is appropriate for the WQPL for practical reasons, including lack of appropriate reference sites, and because the goals of the WQPL are driven by a vision of healthy ecosystem function. Assessment parameters should be based on the goals for the site, practicality of monitoring actions, and budget constraints. Selected parameters should provide insight into the baseline condition of the site and the impact of management action versus inaction. An example of this is the effect of alternative treatments on woody plant cover on the WQPL provided in Appendix 8. Moreover, monitoring should be conducted at multiple spatial and temporal scales (months and years) to be most meaningful. Small scale monitoring is important for illuminating mechanisms of change while large scale monitoring enhances understanding of the context and overall progression of management interventions (Meffe et al. 2002; Whisenant 1999). Additionally, monitoring activities should include both frequent rapid visual assessments over large areas (e.g., seasonal changes in ground cover), and less frequent, more detailed local studies (e.g., fire effects on invasive woody plant species and perennial grasses).

4.1.2 Adaptive Management for the WQPL

The WQPL's primary goal of producing clean water from the owned properties to recharge the Barton Springs segment of the Edwards Aquifer is best achieved by restoring and maintaining properly functioning savanna ecosystems in the recharge zone. Restoring ecosystems to provide a broad array of ecosystem services is a secondary goal. Therefore, assessment parameters that provide data on hydrologic function should be prioritized.

Direct measures of hydrologic function, such as evapotranspiration, infiltration, runoff, hydraulic conductivity, deep drainage, and water balance are most informative and should be obtained whenever possible. However, directly measuring these parameters at large scale is complicated and expensive. A more practical indirect approach is using models that evaluate the delivery of key ecosystem services as functions of community parameters (e.g., recharge as related to perennial grass and woody plant canopy cover). Vegetative composition and structure provide insight into progress toward the attainment of the target community that optimizes the hydrologic function of the site. Therefore, measuring changes in dominant species composition as well as woody, herbaceous, and litter ground cover should be given high priority. These parameters also provide information on the transition of sites between ecological states, such as from open savanna to woodland. Changes in these parameters can signal when gains made by previous management are in danger of being compromised without timely maintenance, or when an area is reaching a point beyond which the ecosystem will likely be difficult to restore. Restoring savannas becomes increasingly challenging and expensive as woody plant cover and height increase and herbaceous cover decreases, because the effectiveness of prescribed fire as a woody plant management tool declines under these conditions. Vegetative community monitoring will help managers anticipate this transition. Assessments of soil surface conditions (physical crusting, erosion, litter, vegetative cover, microbiotic crust cover, and micro-topography) can provide information on hydrologic cycling as well as erosion (Whisenant

1999). Monitoring function is more informative but is expensive and time consuming, so functional assessments should be supplemented with community assessments.

4.2 Prescribed Fire

Prescribed fire is a critically important management tool for the WQPL and needs to be applied more broadly to attain its management goal of restoring and maintaining healthy savanna ecosystems to ensure high yields of quality water recharge to the Barton Springs segment of the Edwards Aquifer. Appropriate fire return intervals differ for well-established savannas versus encroached areas requiring restoration. As described in section 2.2.2.1, early in the restoration process return intervals will need to be 2-3 years to control woody resprouts and consume woody debris. As restoration progresses and woody populations are brought under control, 4-6 years maintenance intervals may be adequate but keeping in mind that historical fire return intervals across central Texas were probably 1-4 years (Guyette et al. 2012). Interannual variation in precipitation and soil depth will determine how long it takes a site to accumulate sufficient fine fuel to burn. Shorter intervals may be necessary in savannas with deeper soils that can support more rapid vegetative regrowth and on sites with a large component of resprouting woody species, while longer return intervals are appropriate for sites with shallower soils that accumulate fuel very slowly. Burning on a particular site should aim for a high frequency if it generates sufficient fine fuels to carry fire effectively, and then burn as soon as possible once a site is in prescription. Because current condition is an ever-changing variable, decisions on return interval, season, and intensity of fire will need to be based on careful monitoring both before and after fire to determine the trajectory of community development. Burn return intervals and target intensities should be determined by the current and target species composition and structure of the site, fuel load, fuel type, soil type and depth, topography, wildland-urban interface concerns, and presence of endangered species.

4.3 Brush Management

Given the different responses of savanna-encroaching woody species to fire, an integrated pest management (IPM) approach that combines prescribed fire, thinning, shredding, and targeted herbivory, as well as herbicide use as last resort, is the best approach for managing the abundance of these species in the WQPL (Hanselka et al. 1999). An IPM plan is currently used in the WQPL and should be applied when undesirable species become problematic. Removal of woody vegetation should be guided by best management practices concerning soil disturbance, herbicide use, and the WQPL's goals. The best management practices in place for the WQPL have been informed by years of experience with the sites; however, continued peer networking and review of scientific and technical literature will allow continued innovations. It should be noted that, if targeted herbivory is included, then using too many goats for too long can detrimentally affect other rangeland forage species that goats will also utilize (Treadwell et al. 2021).

Where woody biomass is high, physical removal should occur in stages to allow recovery time between removal events and to avoid the accumulation of woody debris that can suppress herbaceous plant regeneration. For example, woody populations can be categorized and removed by size class, beginning with the smallest size class. This will simplify slash management and will reduce the fuel load created with each removal event. If on-site burn piles are necessary, they should be located where erosion risk is minimal and, after the piles are burned, the soil surface beneath them should be lightly disked or harrowed in the spring to break the soil crust and then reseeded. Brush thinning activities should be coordinated with prescribed burn planning because such thinning should be followed up with regular prescribed burns to prevent woody plant regrowth.

The percent of woody species recommended to be cut is based on the current woody coverage of the site and the NRCS ecological site description. The target woody cover over the savanna grasslands of the WQPL should be gradually reduced to maximize water yield until it is less than 15%.

Upland areas should be prioritized for brush management using the following criteria:

1. Soils shallow and underlain by fractured geologic substrate (e.g., recharge zone)
2. Areas with ecological site descriptions that indicate a historic plant community of grassland or savanna with a woody cover below 30%.
3. Areas that are tipping from savanna to dense brush, i.e., retain prairie vegetation but have a high percentage of young shrubs or are acquiring characteristics that will make prescribed fire more difficult to apply and less effective (e.g., juniper reaching 5 feet in height coupled with decreasing herbaceous coverage/fine fuels).
4. Current savannas that are less costly to maintain than restoration from dense brush.
5. Property size, distance from developed areas, accessibility, and current uses.

4.4 Riparian Areas

Larger perennial and intermittent waterways should be restored to historical riparian vegetation structures as described in Section 3.3.2.1. Many of the strategies discussed in Section 3.3.2.6 can be successfully employed in riparian areas. Increased native diversity should be encouraged through selective juniper removal and seeding of native woody and herbaceous species. Primary goals guiding species selection in the riparian areas are enhanced bank stability and water quality. Many species found in central and southwest Texas have been given draft stability ratings based on their contribution to bank stability (Nelle 2009). Ideally, riparian areas will be dominated by plants with stability ratings between 6 and 9, with stability ratings of 7 or higher being considered the minimum for acceptable bank stability. However, combinations of species, particularly woody species in association with grasses or sedges, can provide higher stabilities than reflected in individual species ratings (Nelle 2009). In addition to stability ratings, USFWS wetland indicator status should be considered. Riparian areas should contain a mix of obligate wetland, facultative wetland, and facultative species, dependent on water availability. Perennial waterways (generally found in the contributing zone) can support a larger complement of obligate and facultative wetland species, while intermittent waterways (generally found in the recharge zone) generally support a higher proportion of facultative species. Regardless of the mix, it is important that all riparian areas contain some species from the facultative groups to provide stability as water availability fluctuates.

Native woody species are most likely to establish during a flood year (Glenn and Naglar 2005). However, rainfall prediction is difficult so emphasis should be shifted from container grown plants to seeding when adding plant material. Seed can be relatively inexpensively added each year. Cuttings could be used in wetter areas, but most of the riparian areas on these properties will be too dry to allow for their survival.

4.5 Endangered Species Habitat

The potential impacts of the WQPL land management regime to these species will be carefully assessed. Presence/absence surveys are conducted by third-party consultants prior to land management activities to ensure no adverse impacts. The land management recommendations for areas containing occupied Golden-cheeked warbler will adhere to the guidelines outlined for Texas Parks and Wildlife in Campbell (2003).

4.6 Land Cover Categories Management Recommendations

This final section addresses management guidelines for the four land cover categories described in Section 1.6: savanna grassland, savanna woodland, interface savannas and Warbler woodland. Per the overall management guidelines provided in Section 3.2, site selection for brush removal as part of prairie and savanna restoration should be guided by: (1) where most woody cover is encroaching, (2) where terrain is less than 10% slope, and (3) where there is no occupied Golden-cheeked warbler habitat. Additionally, site selection should emphasize upland areas with shallower soils and avoiding soil disturbance by mechanical brush removal and seeding equipment especially near riparian corridors and internal drainage basins associated with karst features. Finally, in the selected areas, enough encroaching woody plants should be removed to attain woody plant cover of less than 30%, which is considered optimal for water quantity and quality generation in the WQPL, while ensuring long-term maintenance of grassland vigor and brush reduction by regularly monitoring vegetation composition. Potential tools for vegetation management include, prescribed fire, mechanical thinning, mowing and haying, targeted grazing, targeted browsing, and limited use of herbicides as described in Section 2.2.

4.6.1 Savanna Grassland

Savanna grasslands are defined by continuous herbaceous cover and periodic surface fires. To maintain this vegetation structure, it is imperative that surface fires are applied at short enough intervals that woody encroachment is halted or reversed. Specifically, vegetation management in these areas should maintain woody cover levels as far below a maximum of 30% on each burn block as is practical. All management units that have been identified as savanna grasslands on the WQPL are appropriate for this target because they are grass-dominated, have woody plant canopy cover levels below 30%, and are greater than 3,000 acres, which is a scale that is conducive to extensive management. At least two factors render savannas difficult to manage when their woody plant canopy cover exceeds 30%. (1) When woody plant canopy exceeds 40% and grass cover falls below 60%, fine fuel connectivity and transmission of surface fires through the landscape decline (Staver et al. 2011b, Staver and Levin 2012, van Ness et al. 2018). While surface fire may carry underneath woody plants in some systems and under some conditions these conditions are not generally met on the WQPL, where surface fuel loading and dryness as well as surface wind speed are reduced under woody plant canopies. Transmission of crown fire between woody plants generally only occurs under conditions that exceed the prescriptions for fire application on the WQPL, which are guided by safety considerations. However, when woody plant (especially juniper) canopy cover increases, the risk of crown fire increases when conditions become conducive for wildfire proliferation (Thomas et al. 2016). (2) In accordance with logistic growth patterns that are frequently observed in biological systems, woody plant encroachment rates are highest at intermediate canopy cover levels (Yang and Crews 2020). Therefore, allowing woody encroachment to progress to more than about 30% canopy cover counters the goal of maintaining savanna grasslands that are optimal for multiple ecosystem services including water yield benefits (Wu et al. 2001, Wilcox 2002). Woody plant cover of 30% is the maximum that is practical for maintaining savanna grasslands, but woody plant canopy cover levels below 15% are recommended for water yield benefit because, at intermediate levels, remaining woody plants can take up the additional water released by prior woody plant reduction treatments (Cardella-Dammeyer et al. 2016). However, it has also been demonstrated that the presence of some woody plants can improve water infiltration, so a completely treeless landscape is not necessary for optimal hydrologic benefit (Leite et al. 2020).

Savanna grasslands on the WQPL should be exposed to moderate intensity surface fires at 2–4-year return intervals. Frequency and intensity should be higher where canopy cover approaches 30% and lower where it is approaches 10%. Mechanical thinning may be useful either where canopy cover exceeds 30% or where sufficient fire frequency and intensity are lacking due to operational or other constraints. Despite multiple thinning and burning treatments, many WQPL savanna grasslands have woody plant canopy cover near 30% dominated by mature trees that are not generally susceptible to prescribed burns and are not targeted for thinning. Canopy cover on these sites may decrease over long periods due to drought and disease vulnerability of mature trees and a lack of sapling recruitment.

Broadcast herbicide treatments are generally not recommended for the savanna grassland areas due to high cost of application and concerns about flushing of broadly applied herbicides into the recharge features. Herbicides are recommended only for use in individual plant treatments where exotic resprouting shrubs are increasing or where introduced species with high invasion potential occur at low levels.

Mowing and haying in the savanna grassland areas are not recommended because they do not benefit the program objectives, and sites are often rocky, partially wooded, sloped, remote, and large. Prescribed fire is the preferred method of disturbance in these areas. Targeted grazing is similarly not recommended. Without substantial fencing and staff investments that would be required for AMP grazing (described in Section 2.2.1.3), inclusion of grazers can promote unpalatable plant species that already dominate due to long-term overgrazing by previous landowners. Additionally, flushing of fecal matter from livestock into recharge features could pollute groundwater and livestock could exacerbate soil erosion and compaction, especially in sensitive riparian areas.

Conversely, targeted browsing is recommended where moderately palatable woody plants that limit fine fuel continuity may be otherwise difficult to manage. Initial treatments should be exploratory and implemented at small scale to determine if they are practical and economical compared to other treatment options. This option may be impractical due to the challenge of containing goats; prescribed fire, mechanical thinning, and selective herbicide applications may prove to be more suitable options for savanna grasslands.

Seeding treatments improve plant diversity and ground cover in disturbed or otherwise exposed areas to minimize soil erosion; therefore, such treatments are an important intervention option for the savanna grassland areas. Seed must be applied directly to soil and, therefore, seeding treatments are most effective following woody plant canopy reduction from fire or mechanical thinning, or on sites where bare soil occurs between native bunchgrasses. Almost all herbaceous species that occur on the WQPL are fire-adapted and typically resprout vigorously from the crown area following top-kill from burning, except for King Ranch bluestem that can suffer high mortality following growing season fires. Many woody species also resprout from their base when top-killed by fire or mechanical thinning, with a notable exception being Ashe juniper, which cannot resprout following top-kill. Where ground cover is substantially reduced by fire and there is a low seed bank, seed can be applied directly to the soil via seed drill or hand broadcast. Grass may not colonize these sites before woody plants unless supplemental seed is applied. Ensuring seed-to-soil contact may require significant labor investment especially where leaf blowers and hand raking are required on sites that are inaccessible to a tractor-mounted seed drill. To ensure effective reseeing, it may also be important to apply seed in multiple years because weather variability in central Texas may diminish the efficacy of a single application of seed. Seeding can also improve plant diversity in undisturbed bare areas between native bunchgrasses in savanna grasslands. This is recommended on sites where diversity is poor or that provide favorable habitat for underrepresented herbaceous species.

4.6.2 Savanna Woodland

Savanna woodlands are generally isolated areas in the WQPL with woody plant cover that exceeds 40% and that are surrounded by savanna grasslands and do not support Golden-cheeked warblers. These areas are generally not conducive to the same management approaches as the savanna grasslands because of abundant mature trees and poor or discontinuous herbaceous cover, but some may become suitable for grassland management in the future, especially with increasing woody plant mortality from stressors associated with climate change. It is recommended that, where possible, savanna woodlands are periodically exposed to fire under safe burning conditions to limit encroachment into adjacent grasslands and improve oak recruitment and understory plant diversity. However, broad ecological benefits associated with fire will be limited because these woodlands generally cannot support effective surface fires, and crown fires should be avoided due to the risk of escape. Occasional mechanical thinning treatments and targeted browsing by goats that promote light penetration may improve surface fuel loads, plant diversity, oak recruitment, and resilience to climate-related stressors including drought and wildfire. As these savanna woodlands are relatively small and often embedded within larger grassland savannas, woodland health treatments are not a primary objective as management resources will be more effectively used in surrounding grasslands. Savanna woodlands are not conducive to mowing, haying, or grazing, and herbicide applications are recommended only where introduced species with high invasion potential occur at low levels.

4.6.3 Interface Savanna

Interface savanna areas are small areas that include both grassland savanna and woodland savanna, but they are differentiated by their proximity to high and medium density residential subdivisions, transportation infrastructure, and other sensitive infrastructure including schools and medical facilities. Fire return intervals of 4 years may be optimal to maintain woody canopy cover, but longer intervals may be appropriate given the complexity and risk exposure of applying fire near developed landscapes. Supplemental mechanical and herbivory treatments may ensure that a 10-year fire return interval is sustainable. Smaller woody plants in interface savannas could be manually removed by volunteers on an annual basis. Given that the interface savanna areas are adjacent to developed areas, they are susceptible to non-native species invasion, herbicide treatments are recommended where introduced species with high invasion potential occur at low levels. These areas also present the greatest risk of damaging wildfires, so mowing, haying, grazing, and browsing may be useful to reduce accumulated fine fuel loads, especially along property boundaries. These treatments may also extend effective fire return intervals in the interface savannas, which releases limited fire resources for use in the grassland savannas where fire is more efficient, more effective, and presents less risk of escape. Some interface savannas have good treatment histories and are in good ecological condition, with minimal noxious species and a high abundance by conservative and endemic species. It would be possible to allocate a significant proportion of program resources to these sites to reduce wildfire risk, and to restore and maintain low canopy cover, high floristic quality, and low noxious species abundance. However, such management interventions would offer relatively limited benefit for the natural resource objectives and would incur a high cost compared to much larger savanna grasslands sites. Importantly, the interface savannas can provide excellent opportunities for community engagement and support from partnering agencies, such as Austin Fire Department, in the management of WQPL areas that are adjacent to developed areas.

4.6.4 Warbler Woodland

Warbler woodlands are those areas in the WQPL where the endangered Golden-cheeked warbler is known to occur. In these areas, canopy reducing treatments are legally not permissible, except for maintaining fence lines and trails. Unfortunately, this prohibition of managed disturbances may render these sites increasingly vulnerable to climate change-related stressors, including severe drought and wildfire. In general, mechanical thinning followed by prescribed fire and targeted browsing treatments could improve the resilience of these woodlands by simulating oak recruitment and mitigating climate-related stressors; however, a special permit from the United States Fish and Wildlife Service would likely be required. Experimental applications of prescribed fire in occupied Golden-cheeked warbler habitat are currently underway at the Balcones Canyonlands National Wildlife

Refuge (Reidy et al. 2021). Prescribed rejuvenation treatments in woodlands are recommended to the extent that they do not compromise the quality of Golden-cheeked warbler habitat and are approved by relevant authorities. Such treatments are consistent with the WQPL mission because drought- or wildfire-related collapse of mature woodland canopies would compromise the quality of water entering the aquifer, as has been demonstrated throughout the western states. Mowing, haying, and grazing are not applicable on these woodlands. Mechanical or herbicide-based independent plant treatments of non-native invasive species are strongly recommended in warbler woodlands and is a management practice for warbler habitat that is actively practiced on protected lands owned by the Nature Conservancy, Balcones Canyonlands Preserve partners, and on military land, notably Fort Hood. Deer culling is another management practice that is actively applied in warbler woodlands managed by other land management agencies to improve plant diversity and oak recruitment, both of which can directly benefit the quality and long-term viability of warbler habitat (Andruk et al. 2014). While deer culling is currently not planned for the WQPL, if it is used in the future, occupied Golden-cheeked warbler habitat should be included.

4.7 Conclusions

This land management plan for the City of Austin's WQPL focuses on the continued supply of high-quality water to Barton Springs. In addition to the high recreation value of the pool fed by these springs, they are also home to the endangered Barton Springs salamander (*Eurycea sosorum*) and the endangered Austin Blind salamander (*Eurycea waterlooensis*). The Barton Springs segment of the Edwards aquifer is characterized by soluble carbonate bedrock that facilitates rapid groundwater recharge and subterranean flow. Fractures along and adjacent to faults along the eastern edge of Edwards Plateau increase recharge and because there is minimal filtration of water entering the aquifer, this leads to water quality sensitivity in the area. Major stream channels crossing the recharge zone contribute about two thirds of groundwater recharge and diffuse upland recharge contributes the remainder. Maintenance of high-quality water in Barton Springs is critical to protect the endangered salamander species and to feed the Barton Springs pool with clean water.

To address conservation concerns over development effects on water that feeds Barton Springs, the City of Austin has purchased 12,041.7 acres in fee title land and 22,132.4 acres of conservation easements in six watersheds in Travis and Hays County. Land management plans for the WQPL fee title properties were developed in 2001 by the Land Management Planning Group and updated in 2012 by the Lady Bird Johnson Wildflower Center to account for new properties and new land management research. In 2021, the City signed an interlocal agreement with the Texas A&M University to fully revise and update the land management plan for the WQPL properties for the period 2022-2032. This agreement specified that the parties will update the Land Management Plan to reflect the most current scientific literature demonstrating that savanna grassland restoration effectively supports environmental integrity and resilience and biodiversity for societal benefit, and to demonstrate how grassland management protects the City’s investment in groundwater supply and quantity, while also supporting a holistic suite of ecosystem services.

To achieve the goal of directing land management to protect water quality and quantity in combination with a broader suite of ecosystem services, specifically maintenance of biodiversity, several management priority areas have been identified. This included managing vegetation to minimize sediments and debris in aquifer recharge water, balancing land use and management options with water quality/quantity protection, reducing contamination of runoff water due to on- and off-site activities, protecting and/or enhancing biodiversity, riparian areas, and riparian buffer strips to enhance water quality, and enhancing the capture of precipitation and its recharge into the aquifer.

The land management plans developed in 2001 and 2012 provided management recommendations based on 1-8 treatment units for each of the nine management areas (fee simple properties). The management recommendations were based on past land use, ecological sites, and physical features, and each was assigned an overall vegetative goal and treatment regime. While these were spatially explicit management recommendations, there was a tremendous amount of duplication of recommendations that did not facilitate application of appropriate land management in a straightforward manner in areas with similar land cover across all management units. To address this limitation of the previous land management plans, this updated WQPL Land Management Plan focuses on four broad landcover categories that occur to various extents across all 11 management units that currently constitute the WQPL fee title properties. The four land cover categories are Savanna Grasslands, Savanna Woodlands, Interface Woodlands, and Warbler Woodlands.

This report documents recommended management options for each land cover category including periodic prescribed fire, mechanical thinning, herbicide applications, mowing and haying, targeted grazing and browsing, and seeding. The use of periodic prescribed fire is the most broadly recommended management practice for maintaining woody plant cover at below 30% and promoting diverse vigorous herbaceous cover capable of carrying surface fire in savanna grasslands. This is followed in importance by mechanical thinning and to a lesser extent herbicide use where woody plant density is approaching the 30% threshold and where exotic invasive woody plants occur in low numbers, respectively. Where canopy cover exceeds 30% in savanna woodlands, periodic application of fire is also recommended but this may be less effective than in more open areas because of less surface-level fine fuel continuity; in these areas mechanical thinning and may be important to open canopies and allow more light penetration to stimulate ground cover. Seeding is also an important management tool especially in areas with low seed banks that have been left bare or disturbed following prescribed fire or mechanical thinning. Mowing and haying may also be useful in Interface Savanna areas where the use of prescribed fire is more challenging due to the higher risk of fire escaping into adjacent developed areas. Finally, targeted browsing with goats is suggested as a possible tool for inhibiting woody plant expansion due to the preference of goats for woody plant sprouts and young plants but this method may not be feasible due to the difficulty of containing goats in target areas. Targeted grazing by cattle and deer culling are currently not recommended as land management options although they may be considered in the future. The Warbler Woodlands that contain occupied Golden-cheeked warbler habitat can, broadly, not be subjected to management treatments, but some organizations are starting to experimentally apply habitat improvement treatments with US Fish and Wildlife Services approval.

Ultimately, Barton Springs and the Barton Springs segment of the Edwards Aquifer are highly valued features that need permanent protection from the deleterious effects of rapid development in surrounding areas. Due to the poor filtration capacity and rapid flow of water within karst geology, such development has compromised the water quality at Barton Springs and the endangered salamander species that inhabit them. The WQPL consist of strategically purchased properties by the City of Austin in the contributing and especially in the recharge zones to protect from contamination the supply of high-quality water that discharges from Barton Springs. Proper land management of these properties to maintain healthy and resilient savanna grasslands, which historically dominated the area, is imperative if the goal of maintaining high water quality in the aquifer is to be achieved. This management goal will become increasingly important in the face of predicted climate change increases in extreme weather events, including episodic severe drought and high rainfall events that are likely to impact recharge of the aquifer. This management plan provides guidelines for managing these properties in a practical manner by applying best management practices to attain the stated goal of maintaining high quality water supply most efficiently.

Section 5
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5 Bibliography

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Section 6
Appendices

6 Appendices

6.1 Appendix 1: Karst Management on the Water Quality Protection Lands

6.2 Appendix 2: Distribution of Endemic Plants in the Eastern Edwards Plateau Relative to Three Categories of Shading.

6.3 Appendix 3: Targeted Herbivory Services Agreement

6.4 Appendix 4: Benefit-Cost Analysis of the Water Quality Protection Lands

6.5 Appendix 5: Water Quality Protection Lands Climate Change Projections

6.6 Appendix 6: Water Quality Protection Lands Equitable Community Engagement

6.7 Appendix 7: Wildfire Prevention Plan

6.8 Appendix 8: Woody plant response to treatment on the Water Quality Protection Lands

Appendix 1: Karst Management on the Water Quality Protection Lands

Introduction

The WQPL is located on karst terrain, which are landscapes underlain by soluble carbonate bedrock and include caves, sinking streams, aquifers, and springs. Karst systems support rapid groundwater recharge, preferential flow pathways, shallow soils, and clay soils that crack with desiccation (Ford and Williams 2007). Karst features on the WQPL, including caves, springs, and aquifers, also support habitat for threatened, endangered, and declining wildlife species, including Eurycea salamanders, tricolored bats, and many narrowly endemic invertebrates. Hydrologic and biological function are both highly sensitive to anthropogenic degradation in karst landscapes, a fact which underlies the necessity of the WQPL to protect critical environmental resources. Land management on the WQPL must emphasize karst management to conserve and improve both hydrologic and biological function as core program goals.

Historic land use on the WQPL compromised and degraded critical hydrologic and biological functions of the underlying karst geology. Historic land use on the WQPL was dominated by ranching between the mid-19th and mid-20th centuries, and ranchers would a) fill caves (to dispose of trash, protect livestock from injury, and hold water at the surface), and b) overgraze the land. Cave filling would directly obstruct groundwater recharge and degrade karst habitat, and overgrazing, in conjunction with the extreme weather fluctuations between drought and flood that typify central Texas landscapes, induced erosion and sedimentation, and would thus indirectly also obstruct groundwater recharge and degrade karst function.

Contemporary land use in watersheds that drain to the Barton Springs segment of the Edwards Aquifer also degrade critical hydrologic and biological functions of the underlying karst geology. Overharvesting water, contamination from nutrients and pathogens from multiple forms of effluent discharge, erosion and sedimentation from active construction sites, and non-point source pollution from various forms of development and land use change all degrade recharge capacity and water quality.

Many karst features have been documented on the WQPL; however, many more undoubtedly remain undiscovered. In most cases, karst features have been filled by erosion and sedimentation or trash disposal, which often makes them difficult to recognize. Also, dense vegetation cover may make small features difficult to locate even if they remain open. Formal karst surveys have been conducted on a small fraction of the WQPL, for example prior to trail siting, and virtually every karst feature survey yields new features. Of those features that have been located, few have been properly excavated.

Karst management consists of a limited toolkit of interventions; a) excavation, which improves surface connectivity with karst environments, b) protection, which consists of physical barriers to limit accessibility (for example, by trespassers) or obstruction due to sedimentation or similar impacts, and c) karst feature surveys, which is a process of inventorying the geographic location of karst features to prioritize excavation and protection efforts.

Karst management on the WQPL must satisfy multiple conservation objectives (hydrological and biological) from multiple sources of degradation (historic ranching and contemporary development). A tiered approach is useful to classify appropriate management strategies for karst features based on where they occur on the landscape and what threats are present and solutions are applicable. Three discrete varieties of karst feature exist for the purposes of prioritizing management: riparian, internal drainage basins, and upland.

Conservation targets: riparian, internal drainage basin, and upland karst features

Riparian karst features, that is, those located in creek bottoms and flood plains, have the greatest potential to facilitate groundwater recharge. This class of karst feature can provide continuous groundwater recharge throughout the duration of stream flow events, and the rate and yield of these events is limited by the minimum aperture diameter of the feature. These are therefore the highest priority sites to restore recharge function via excavation, protection and ongoing maintenance, and these kinds of land management interventions are the most potent and direct tool available to benefit the primary WQPL program mandate to restore and protect groundwater recharge. As stream order increases, so does a) absolute volumetric streamflow and thus potential groundwater recharge volume, and b) potential exposure to pollutants from unprotected lands upstream from the WQPL. Current practices to balance that potential tradeoff between groundwater recharge quality and quantity on the WQPL is comprised of excavating sediment to restore volumetric recharge capacity and concurrently installing swallet gates with expanded metal mesh coverings (Figure 1) to prevent accumulations of sediment.

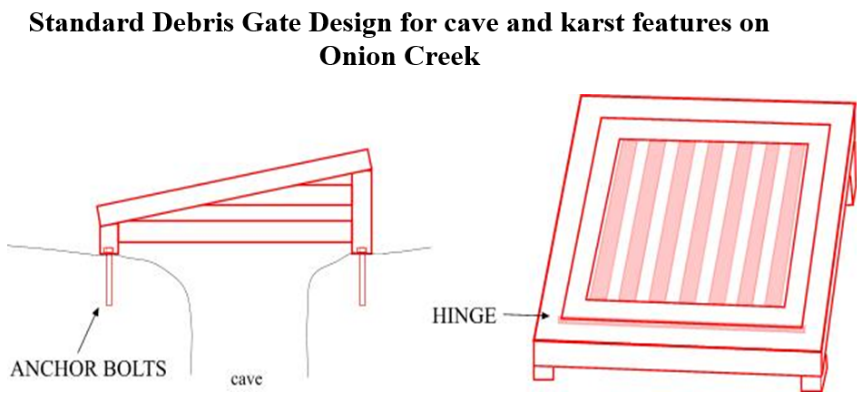

Figure A1.1. Debris gate design for cave features at Onion Creek

These coverings are remarkably effective at self-sealing, especially during flood events (which provide the bulk of low-quality water), but also require regular maintenance during flow periods to facilitate continued recharge (Figure 2). Antioch cave, which is located just downstream of the WQPL in the bed of Onion Creek and is managed by the Barton Springs Edwards Aquifer Conservation District (BSEACD), also balances the tradeoff between groundwater recharge quantity and uses an automated system which excludes flows with a total suspended solid load above a certain threshold (50 PPM). WQPL staff have coordinated with BSEACD staff to compare the mesh cover clearing schedule with that of the automated system at Antioch and learned that the normal threshold for WQPL staff to clear mesh coverings, based on a visual estimate of water clarity, is significantly lower and occurs later after peak flood conditions, generating higher quality recharge with a modest sacrifice of quantity.

Figure A1.2: Sequence showing (a) cave gate sealed with organic debris after flooding, (b) mesh covering removed for cleaning, and (c) mesh covering reinstalled after cleaning.

Labor inputs for clearing these mesh coverings is as a limiting factor. The mechanism by which these mesh coverings exclude polluted water during flood events is the accumulation of dead plant biomass (mostly fallen leaves) that are larger and more mobile in the water column compared to suspended sediment and other flood debris that could clog recharge features. Once this residue is manually cleared, karst features recharge with high quality water until another layer of leaves accumulates and effectively seals the cave again. Predictions that caves will seal with flood events and discrete leaf drop events such as from deciduous trees in late fall and live oaks in late winter have proven reliable and robust, however, plant material can accumulate and seal mesh coverings during any prolonged flow event, even if no discrete leaf drop or flood event occurs. This issue creates a substantive maintenance task which, if neglected, can hinder the recharge capacity of swallets that are protected with fine debris covers during surface flow events. For example, Onion Creek had prolonged flow periods during the spring and summer months of 2015 and 2016, and WQPL staff visited swallets multiple times per month and found caves had often resealed with organic debris in the absence of major flooding or discrete leaf drop events. Since then, program policy has shifted to mandate multiple staff present for this maintenance task in response to safety concerns, and staff availability tends to delay maintenance visits, reduce the frequency of visits, and as a result, hinder recharge capacity during prolonged flow periods. It is recommended that additional Wildland Conservation Division staff or volunteers be trained in swallet maintenance and that maintenance visits are made more frequently during prolonged flood events in the future.

Some swallets are not conducive to self-sealing mesh coverings. For example, Disappointment Feature, Inn Below Onion Creek, and Crooked Oak Cave have been prone to taking large volumes of pea gravel that can significantly hinder the flow rate and can only be removed manually and at great expense. Both features are located along the centerline of the riparian channel (thalweg) and in pool reaches of the creek, in contrast to almost all other major known discrete recharge features in Onion Creek, which are located along the banks and in runs, where the self-sealing mechanism of expanded metal fine debris filters functions well. Recharge features in the thalweg of pool reaches may be predisposed to accumulate pea-gravel sized sediment and thus may not be conducive to expanded metal fine debris filters. WQPL staff have implemented two experimental solutions to this problem. Crooked Oak Cave has a sheet metal cover blocking the aperture, which significantly restricts recharge unless it is left open and therefore highly vulnerable to sedimentation in the event of flooding. Disappointment Feature has a more complicated structure (Figure 3) that excludes low flows but allows recharge of water during flows when the depth is greater than approximately 16”. Suction pulls water upwards through downward-facing expanded metal mesh, and a lip forces water along a circuitous pathway.

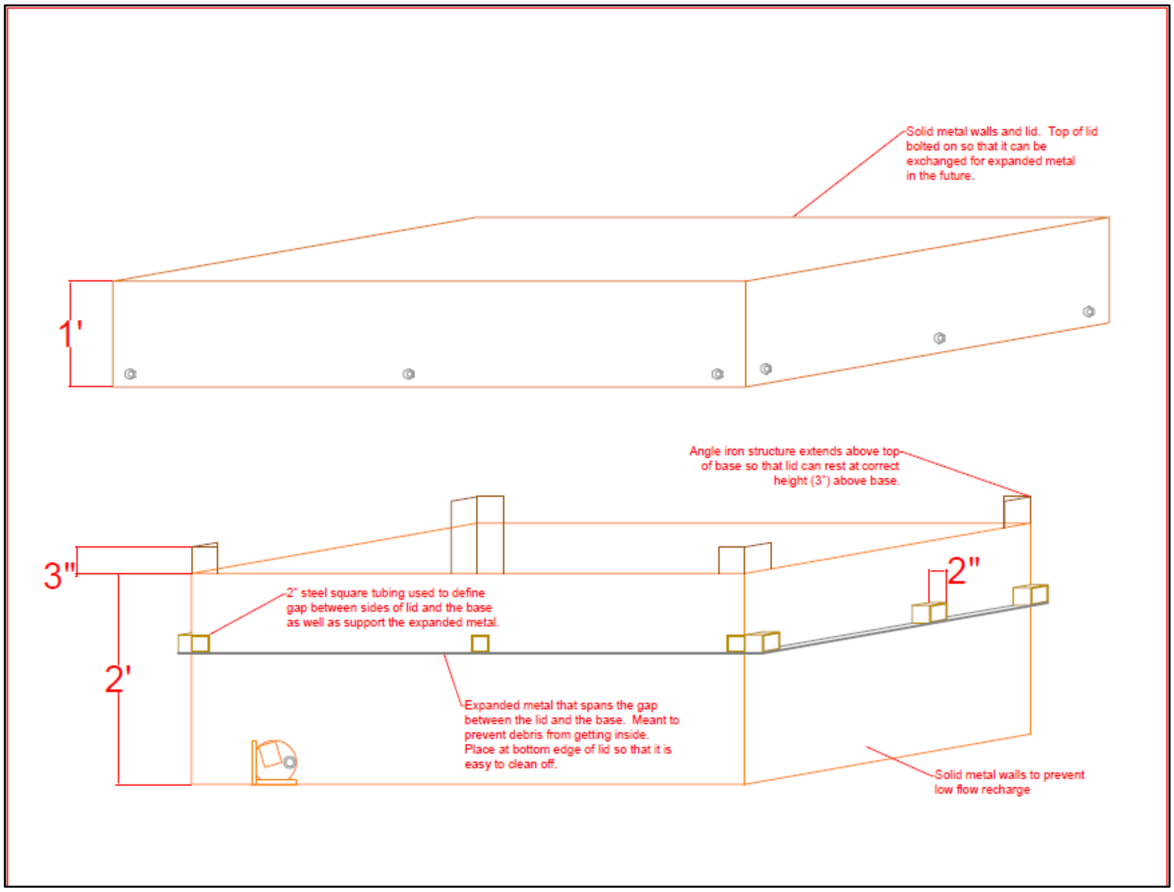

Figure A1.3. Structure at Disappointment Feature that excludes low flows but allows recharge of water during flows when the depth is greater than approximately 16".

This device was designed by consulting engineers from the City of Austin Watershed Protection Department to force pea-gravel and larger sized sediments out of the water column before entering the swallet. This device has performed well in preventing sedimentation in the swallet, however its overall performance in facilitating recharge (and the applicability of the design to other caves in the area) remains yet untested as of October 2022. This is because Onion Creek has not had prolonged flows of adequate depths since the device was installed and the cave was subsequently excavated. It is recommended that during and after the next prolonged flow period on Onion Creek, performance of the structure at Disappointment Feature is carefully evaluated. If it functions well, both in facilitating recharge and excluding sediment, the design could be replicated at Crooked Oak and Inn Below Cave. If not, additional modifications should be made and tested before the design is replicated at Crooked Oak Cave. A distinct set of challenges occurs at Toad Terminal Cave, another swallet in the bed of Onion Creek that was discovered recently and initially excavated in summer of 2021. Little of the surface aperture or cave interior are composed of competent bedrock, and the excavated portion of the cave remains vulnerable to collapse during excavation projects and extreme flooding events. It is recommended that further excavation projects are executed with the utmost of caution, and that if the existing flow pathway cannot be secured via excavation alone, subsurface structural improvements, including but not limited to preformed concrete culverts, be considered.

Discrete recharge features also occur in higher order riparian corridors including upland drainages, such as at Tabor Crevice, Hays County Bat Cave, and many others. These caves may be gated to prevent trespass but have not required fine debris covers as recharge events are very brief and sediment/leaf loads from these protected uplands are apparently very low. These features are good targets for excavation to improve hydrologic function and habitat for troglophilic, troglobitic and stygobitic species. Some of these features support large populations of cave myotis bats, cave crickets, and diverse populations of narrowly endemic and perhaps undescribed species of troglobitic invertebrates.

Discrete recharge features located in internal drainage basins, such as Flint Ridge Cave and Headquarters Flat Sink, are also good targets for protection and excavation to benefit hydrologic and biological objectives. These features have similar flow regimes as karst features located in upland drainage channels, but also have the potential to generate higher yields because they can collect a large percentage of surface runoff, which can be substantial during high intensity rainfall events or prolonged rainy seasons. Despite extreme flooding, some of these environments support robust populations of cave crickets and endemic karst invertebrates, including species that were formally listed as endangered or as species of concern, and species that are likely undescribed.

Upland karst features refer to those that do not take runoff from drainages or internal drainage basins. These may be assumed predominantly important for biological function and should be excavated and protected to improve habitat for troglobitic and troglophile species. Such excavation projects do not likely improve or protect groundwater recharge, but also won't negatively them. Karst management projects in uplands are therefore more motivated by responsible natural resource management to conserve biodiversity on the last few remaining natural areas in an extensively degraded and rapidly developing region. This is particularly critical for karst ecosystems which are narrowly endemic to such an extreme degree with some species known from only a single small cave, and distances between caves of less than 10 miles representing perhaps millions of years of evolutionary separation between species of the same genus. It is possible that upland karst features may connect to critical subsurface flow pathways, and it is therefore possible that excavating upland features could improve subsurface hydrologic function if they clear obstructions to such pathways, but this has not been documented on the WQPL to date.

Karst feature location surveys

The Texas Commission on Environmental Quality provides a formal protocol to survey for the presence of karst features (TCEQ 2007). This protocol specifies a fixed distance of fifty feet between surveyors who walk linear transects to visually scan the land surface for potential karst features. Due to visual obstructions from vegetation and historic cave filling, a spacing of twenty-five feet between surveyors has proven necessary on the WQPL, and this is the preferred distance. These surveys have typically been conducted in areas where development impacts are anticipated, such as on the Hudson tract (aka "Jeremiah Ventures") prior to acquisition by the WQPL, and in the corridor where construction for the Violet Crown Trail is proposed to traverse much of the interior of the WQPL. According to field surveyors, these kinds of surveys have been far more effective immediately following prescribed burns, and to a lesser extent, thinning projects. It is recommended that additional karst feature surveys are conducted following prescribed burns and that excavation projects are pursued where significant features are found. Volunteers can become a part of this work as well.

The Little Bear Creek Recharge Enhancement Project – Wenzel Tract

A unique approach to water quantity recharge on the Water Quality Protection Lands is part of a large-scale experiment with the Watershed Protection Department at a former quarry site known as the Wenzel or Stoneledge quarry (Figure 4). The property is 84 acres in size and the quarry occupies about one-third of the property, with the quarry situated in the central portion of the property. The depth of the quarry excavation ranges from 40 to 60 feet.

The side walls of quarry consist of Kirschberg member geology, one of the most permeable units in Edwards aquifer outcrop. Two pools of water are present in the bottom of the quarry. The most northern pool is a water table pool of the Edwards Aquifer. It is believed this connection between the surface and subsurface was established because of the quarrying operation where explosives may have cracked the rock allowing water from below to rise to the surface and form the lake. Thus, this lake is a direct connection to the aquifer below. As a result of this direct connection to the aquifer and the optimum site-specific geology, the quarry is well suited for recharge enhancement facility. To verify a connection to Edwards Aquifer, the City of Austin's Watershed Protection completed a dye trace study in 2017. The finding confirmed a hydrologic connection between the quarry area with Barton Springs. Initial tracer arrival time at Barton Springs suggested some rapid groundwater flow toward the springs, but persistent detection of tracers in wells suggests that water does move into storage and may persist for up to a year. This indicates a long-term benefit for recharging water to the aquifer and aquifer users from the diverting runoff into the quarry allowing for additional surface water recharge into the Barton Springs segment of the Edwards Aquifer.

Figure A1.4. Aerial view of Wenzel quarry showing the exposed aquifer water.

Since 2004, the city has worked to design and engineer the connection between the quarry and nearby Little Bear Creek to diver flood flows from the creek to the quarry (Figure A1.5). In October 2022, the City of Austin received a water use permit to divert 486 acre-feet of water per year from Little Bear Creek for storage in the quarry for subsequent recharge of the Barton Springs segment of the Edwards Aquifer. The city will divert water from Little Bear Creek via a diversion channel, connected to the quarry, that will limit diversions to approximately 50% of stream flows more than 50-cfs. Based on an Interlocal Agreement between the City of Austin, Lower Colorado River Authority (LCRA) and Barton Springs/Edwards Aquifer Conservation District, the LCRA will reserve 40.2 acre-feet of water per year, on a 50-year term basis, for use in the Little Bear Creek Recharge Enhancement Project, to account for any reduction of run-of-river flows to LCRA downstream senior water rights, for environmental flows purposes, and to account for evaporative losses. The Little Bear Recharge Enhancement Project is schedule for construction to begin in Fall of 2023 with project to complete construction by Spring 2024.

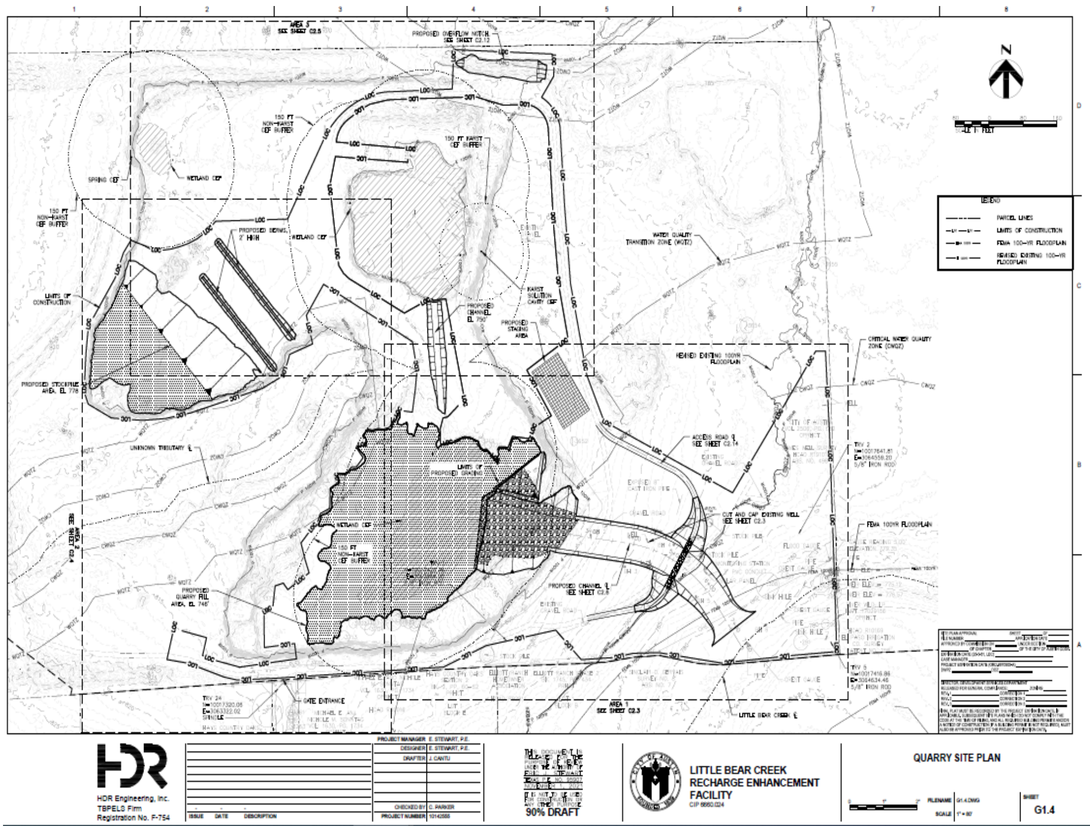

Figure A1.5. Diagram of proposed connection between Wenzel quarry and nearby Little Bear Creek with the idea of diverting flood flows from the creek to the quarry.

References

Ford, D., P.D. Williams. 2007. Karst Hydrogeology and Geomorphology. Wiley & Sons, NY.

TCEQ. 2007. Optional enhanced measures for the protection of water quality in the edwards aquifer and related karst features that may be habitat for karst dwelling invertebrates: Appendix B to RG-348—Complying with the Edwards Aquifer Rules: Technical Guidance on Best Management Practices. Texas Commission on Environmental Quality, Austin, Texas

Appendix 2: Distribution of Endemics Plant in the Eastern Edwards Plateau Relative to Three Categories of Shading.

Seventy-one Texas endemics known from the eastern Edwards Plateau and their typical distribution across the landscape relative to three categories of shading: (1) full shade – closed-canopy vegetation with extensive areal coverage [closed canopy woodland]; (2) partial shade – broken-canopy vegetation [savanna]; and (3) no shade – grasslands and other types of vegetation with minimal canopy coverage. Many species occur in more than one category, as indicated in the columns below and totals for categories and category pairs are provided at the top of the table. Placement in categories was based on observations of the table author (William Carr) during extensive field work between 1981 and 2019

Scientific Name	Common Name(s)	Full Shade	Partial Shade	No Shade
Agalinis edwardsiana	Plateau gerardia			X
Argemone aurantiaca	Hill pricklypoppy			X
Astragalus crassicarpus var. *berlandieri*	Berlandier ground-plum			X
Astragalus reflexus	Texas milkvetch			X
Astragalus wrightii	Wright's milk-vetch			X
Brickellia dentata	Gravelbar brickellbush			X
Brickellia eupatorioides var. *gracillima*	Narrowleaf brickellbush			X
Castilleja purpurea var. *lindheimeri*	Lindheimer's paintbrush			X
Cryptantha texana	Texas hiddenflower			X
Dalea hallii	Hall's prairie-clover			X
Dalea tenuis	Stanfield prairie-clover			X
Desmanthus reticulatus	Netleaf bundleflower			X
Euphorbia peplidion	Low spurge			X
Gutierrezia amoena	Shinners' broomweed			X
Ipomoea costellata var. *edwardsensis*	Edwards Plateau morning-glory			X
Lechea san-sabeana	San Saba pinweed			X
Liatris glandulosa	Glandular blazing-star			X
Packera texensis	Llano butterweed			X
Pectis angustifolia var. *fastigiata*	Crownseed pectis			X
Pediomelum cyphocalyx	Turnip-root scurfpea			X
Pediomelum hypogaeum var. *scaposum*	Stemless scurfpea			X
Pediomelum latestipulatum var. *appressum*	Broad-stipule scurfpea			X
Physaria densiflora	Denseflower bladderpod			X
Physaria engelmannii subsp. *engelmannii*	Engelmann's bladderpod			X
Physaria recurvata	Plateau bladderpod			X
Silphium albiflorum	White rosinweed			X
Tradescantia subacaulis	Stemless spiderwort			X
Triodanis texana	Texas Venus' looking-glass			X
Corydalis curvisiliqua subsp. *curvisiliqua*	curvepod corydalis		X	
Ditaxis aphoroides	Hill Country wild-mercury		X	

Scientific Name	Common Name(s)	Full Shade	Partial Shade	No Shade
Malvastrum aurantiacum	Golden falsemallow		X	
Phlox pilosa subsp. *latisepala*	Rough phlox		X	
Phlox pilosa subsp. *riparia*	Texas phlox		X	
Polytaenia albiflora	Whiteflower prairie-parsnip		X	
Streptanthus bracteatus	Bracted twistflower		X	
Streptanthus petiolaris	Brazos rockcress		X	
Vitis monticola	Mountain grape		X	
Amorpha roemerana	Texas amorpha		X	X
Buddleja racemosa	Wand butterfly-bush		X	X
Chaetopappa bellidifolia	Hairy least-daisy		X	X
Chaptalia texana	Nodding lettuce		X	X
Daucosma laciniatum	Meadow daucosma		X	X
Dichondra recurvata	Tharp's ponyfoot		X	X
Euphorbia roemeriana	Roemer's spurge		X	X
Galactia texana	Texas milkpea		X	X
Muhlenbergia involuta	Canyon muhly, hybrid muhly		X	X
Nolina lindheimeriana.	Lindheimer's nolina		X	X
Penstemon guadalupensis	Guadalupe penstemon		X	X
Penstemon triflorus subsp. *triflorus*	Scarlet penstemon		X	X
Phlox roemeriana	Golden-eye phlox		X	X
Prunus minutiflora.	Texas almond		X	X
Seymeria texana	Texas seymeria		X	X
Tradescantia humilis	Texas spiderwort		X	X
Yucca rupicola	Twistleaf yucca		X	X
Anemone edwardsiana	Canyon anemone	X	X	
Carex edwardsiana	Canyon sedge	X	X	
Chaetopappa effusa	Spreading least-daisy	X	X	
Clematis texensis	Scarlet leatherflower	X	X	
Croton alabamensis var. *texensis*	Texabama croton	X	X	
Ditaxis simulans	Tall wildmercury	X	X	
Lithospermum helleri	Heller's marbleseed	X	X	
Matelea edwardsensis	Plateau milkvine	X	X	
Parthenocissus heptaphylla	Sevenleaf creeper	X	X	
Phaseolus texensis	Canyon bean	X	X	
Ruellia drummondiana	Drummond's ruellia	X	X	
Styrax platanifolius subsp. *platanifolius*	Sycamore-leaf snowbells	X	X	
Styrax platanifolius subsp. *stellatus*	Hairy sycamore-leaf snowbells	X	X	
Tradescantia edwardsiana	Plateau spiderwort	X	X	
Tragia nigricans	Darkstem noseburn	X	X	
Tridens buckleyanus	Buckley tridens	X	X	
Verbesina lindheimeri	Lindheimer's crownbeard	X	X	

Appendix 3: Targeted Herbivory Services Agreement

THS TARGETTED HERBIVORY SERVICES AGREEMENT (hereinafter referred to as "AGREEMENT") is entered into this day of ____________________, between and among ____, of ____________________ (hereinafter referred to as "COMPANY") and The City of Austin Water and Wastewater Utility (hereinafter and referred to as "CLIENT").

RECITALS:

A. Whereas COMPANY is experienced in providing the Services (as hereinafter defined).

B. Whereas CLIENT has the authority to grant COMPANY lawful possession of, use of, and/or access to the property located at: ______________________________________

____

____

(hereinafter referred to as "PROPERTY").

C. Whereas CLIENT desires that COMPANY perform the Services set forth in this AGREEMENT.

AGREEMENT:

NOW, THEREFORE, in consideration of the mutual promises, covenants, and agreements contained in this AGREEMENT, and other good and valuable consideration, the receipt and sufficiency of which is hereby acknowledged, the parties agree as follows:

I. EXCLUSIVE APPONTMENT

CLIENT engages COMPANY exclusively to perform the Services for the benefit of CLIENT in accordance with, and subject to the terms and conditions of, this AGREEMENT. COMPANY shall provide such Services throughout the term of this AGREEMENT and may also perform similar services for others if COMPANY so desires.

II. TERM

A. <u>Effective Date and Commencement of Services</u>. This AGREEMENT shall become effective on the date set forth above (hereinafter referred to as the "Effective Date"), and CLIENT and COMPANY agree that only the Services provided after the Effective Date shall be subject to the terms and conditions of this AGREEMENT.

B. <u>Term</u>. Unless terminated earlier pursuant to the terms and conditions of this AGREEMENT, or by mutual AGREEMENT of the parties, this AGREEMENT will terminate upon completion of the Services by COMPANY and payment in full of any and all amounts owed by CLIENT to COMPANY, as hereinafter specified.

III. SERVICES

COMPANY shall perform the following services for CLIENT (herein collectively referred to as the "Services") upon the terms and conditions set forth and for the compensation set forth herein:

A. COMPANY shall place live goats upon the Property, or upon designated portions of the Property, for purposes of weed control and/or fire control as more particularly described in Paragraph Ill(B) below. COMPANY shall place as many goats upon the Property as COMPANY, in its sole discretion, deems are necessary or convenient for completion of the Services to be provided hereunder. Upon completion of the Services, and/or upon termination of this AGREEMENT, COMPANY shall cause said goats to be removed from the Property.

B. COMPANY shall place goats upon the property for the following purposes:
____
____
____
____
____

C. During the term of this AGREEMENT, COMPANY may place, construct, and/or erect upon the Property, or any portion thereof, fences or other enclosures, including but not limited to electric fences, and/or any other structures, vehicles, and/or devices deemed necessary or convenient by COMPANY for the performance of the Services hereunder. COMPANY shall be solely responsible to maintain and/or upkeep any such fences, enclosures, structures, vehicles, and/or devices during the term of this AGREEMENT. Upon completion of the Services, or upon termination of this AGREEMENT, COMPANY shall cause any such fences, enclosures, structures, vehicles, and/or devices to be removed from the Property. CLIENT shall not move, alter, modify, damage, or otherwise interfere with any such fence, enclosure, structure, vehicle, and/or devices placed on the Property by COMPANY.

IV. CLIENT WARRANTIES

A. Right to Access. CLIENT hereby warrants and represents that CLIENT has the lawful right to grant COMPANY possession of, use of, and/or access to, the Property for purposes of this AGREEMENT, and that CLIENT will defend COMPANY's possession of, use of, and/or access to, the Property against any and all persons whatsoever. CLIENT hereby waives any claim(s) which it might have against COMPANY arising out of COMPANY's possession of, use of, and/or access to the Property for purposes of this AGREEMENT.

B. CLIENT Interference. CLIENT hereby warrants and agrees that CLIENT shall not intentionally hinder, prevent, obstruct, delay, or otherwise interfere with COMPANY's possession of, use of, and/or access to the Property and/or completion of the Services to be provided hereunder, nor shall CLIENT allow, permit, or enable other persons to do so.

C. Unique Services. CLIENT acknowledges and agrees that the Services provided by COMPANY are of a special, unique, unusual, and unpredictable character, and that the performance and/or completion of said Services may be hindered, delayed, or otherwise affected by factors beyond COMPANY' s control. As such, CLIENT hereby agrees that any delay or failure by COMPANY to perform and/or complete the Services resulting from factors beyond COMPANY's control shall not constitute a breach of this AGREEMENT for which CLIENT is or may be entitled to damages.

V. COMPENSATION

A. Payment of Compensation. In consideration of the Services provided by COMPANY hereunder, and for other good and valuable consideration, the receipt and sufficiency of which is hereby acknowledged CLIENT shall pay to COMPANY not less than $_______________ (hereinafter referred to as the "Compensation"), all of which shall be paid to COMPANY in one lump-sum payment within thirty (30) days after completion of the Services.

B. Late Fees. Should CLIENT fail and/or refuse to pay COMPANY as set forth in Paragraph V(A) above, CLIENT shall pay to COMPANY, in addition to any unpaid Compensation owed by CLIENT to COMPANY, interest equivalent to ten percent (10%) of the unpaid balance owed to COMPANY, which interest shall accrue monthly and shall be paid to COMPANY until all amounts due and owing to COMPANY have been paid in full.

C. Modification of Compensation. The Compensation payable to COMPANY may be modified only by the written mutual AGREEMENT of COMPANY and CLIENT, which written mutual AGREEMENT shall be signed and dated by a duly authorized agent of both COMPANY and CLIENT. Unless otherwise specified to the contrary, such a modification, if any, shall in no way alter or affect any of the remaining terms and conditions of this AGREEMENT.

VI. TERMINATION

A. Default by CLIENT. In the event that CLIENT is in material default or breach of any of the provisions of this AGREEMENT, COMPANY shall have the right to terminate this AGREEMENT upon fifteen (15) days written notice to CLIENT; provided, however, that if CLIENT, within said fifteen (15) day period, cures the said default or breach, this AGREEMENT shall continue in full force and effect.

B. Effect of Termination. Termination of this AGREEMENT for any cause or reason whatsoever shall not be construed to release CLIENT from any payment obligation which has matured prior to the effective date of such termination. Upon termination of this AGREEMENT, COMPANY shall immediately be paid for any Services provided by COMPANY to CLIENT, including, but not limited to, the unpaid portion of any Compensation to which COMPANY may be entitled.

VII. MISCELLANEOUS

A. Indemnification. CLIENT agrees to indemnify COMPANY against, and hold COMPANY harmless from, any and all claims, liabilities, causes of action, damages, expenses, costs of defense (including attorney(s) fees and court costs), and other costs arising out of or in any way related to the Services provided by COMPANY hereunder.

B. Independent Contractor Relationship. The relationship between COMPANY and CLIENT hereunder shall at all times be that of independent contractor, and nothing contained herein shall render or constitute the parties joint venturers, partners, agents, or fiduciaries of each other. Neither COMPANY nor CLIENT shall hold itself out to third parties other than as set forth herein.

C. Disclaimer of Warranties. COMPANY makes no expressed or implied warranties with regard to the Services provided by COMPANY hereunder, and COMPANY expressly disclaims any and all warranties, whether expressed or implied, with regard to the Services provided by COMPANY hereunder.

D. Compliance with Law. In the performance of this AGREEMENT, COMPANY and CLIENT agree that they will comply with all statutes, ordinances, laws, rules, regulations, orders, and requirements of any federal, state, or municipal government.

E. Notices. All notices required or permitted to be given hereunder shall be in writing, and shall be valid and sufficient if dispatched by (i) registered or certified mail, postage prepaid, in any United States Post Office; (ii) hand delivery; (iii) overnight courier; or (iv) facsimile transmission upon confirmation of receipt by the recipient. The address of record for each party shall be as follows:

COMPANY:	**CLIENT:**
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________

F. Serviceability. If any part of this AGREEMENT is determined to be void, invalid, inoperative, or unenforceable by a court of competent jurisdiction, or by any other legally constituted body having jurisdiction to make such determination, such determination shall not affect any other provision hereof, and the remainder of this AGREEMENT shall be effective as though such void, invalid, inoperative, or unenforceable provision were not contained herein.

G. Entire Agreement. The terms set forth in this AGREEMENT, and all attachments hereto, if any, constitute the entire AGREEMENT between COMPANY and CLIENT, all prior negotiations and understandings being merged herein. CLIENT represents that no person acting or purporting to act on behalf of COMPANY has made any promises or representations upon which CLIENT has relied except those expressly found herein.

This AGREEMENT may only be altered by a written instrument executed by both COMPANY and CLIENT.

H. Binding Effect. This AGREEMENT shall inure to the benefit of, and shall be binding upon, the parties hereto, as well as the parties' heirs, personal representatives, successors, and assigns.

I. Further Instruments. The parties hereto agree that they will execute any and all other documents or legal instruments that may be necessary or required to carry out and effectuate all of the provisions of this AGREEMENT.

J. Waiver. No failure by COMPANY to insist upon the strict performance of any provision of this AGREEMENT, or to exercise any right or remedy to which COMPANY may be entitled, shall constitute a waiver of such breach or any subsequent breach, or a waiver of such right or remedy. No waiver of any breach shall affect or alter this AGREEMENT.

K. Gender. Whenever the singular number is used in this AGREEMENT, and when required by the context, the same shall include the plural, and the masculine gender shall include the feminine gender.

L. Capitalized Terns. Capitalized terms used in this AGREEMENT shall have the meanings as defined herein.

M. Clause Headings. The clause headings of this AGREEMENT are for convenience of reference only, and in no way define, limit, or describe the scope or intent of this AGREEMENT, or in any other way affect this AGREEMENT.

N. Attorney(s) Fees. If any action or proceeding is instituted between the parties hereto to enforce any of the terms and conditions of this AGREEMENT, the prevailing party shall be entitled to recover from the other party reasonable attorney(s) fees and costs incurred as a result of such proceeding.

O. Governing Law. This AGREEMENT shall be deemed to have been made in the State of Texas, and its validity, construction, breach, performance, and operation shall be governed by the laws of the State of Texas. Any and all actions brought to enforce this AGREEMENT, or any provision hereof, shall be brought in the State of Texas, and the parties hereby submit themselves to the jurisdiction of the courts of the State of Texas.

IN WITNESS WHEREOF, the parties hereto have executed this AGREEMENT as of the day and year first above written.

COMPANY:	**CLIENT:**
By:______________________________	By:______________________________
Its:______________________________	Its:______________________________

Appendix 4: Benefit-Cost Analysis of the Water Quality Protection Lands

Introduction

In the preceding report, it was documented that woody plant removal can have varying effects on water yields depending on underlying geology and prevailing climatic conditions (Section 3.2). Based on the current understanding of rangeland ecohydrology, it is reasonable to assume that groundwater recharge in the WQPL can be increased by removing woody plants and maintaining high-quality grass cover. The basis for this assumption are: (1) Rainfall and aridity index of the eastern Edwards Plateau are similar to the Cross Timbers and the Post Oak Savanna ecoregions where woody plants substantially increase evapotranspiration and thus reduce streamflow and groundwater recharge; (2) some woody cover, which can benefit soil infiltrability, will persist on the WQPL, and in areas where woody cover is reduced, soils can retain the high infiltrability attributes created by prior woody plant encroachment; (3) grazing pressure is minimal in the WQPL fostering lush mid and tall grasses with lower evapotranspiration than woody plants and that maintain high soil infiltrability. Based on these findings, the following document provides the steps for an approach to determine the economic efficacy of woody plan removal on water yields in the four primary cover types found in individual WQPL units (parcels of fee simple land managed by the City of Austin's Water and Wastewater Utility).

Definitions

Benefit-Cost Analysis (BCA) is a method that can be used to determine the future risk reduction benefits of a hazard mitigation project. It compares a project's future benefits and costs over a specified period using equation 1 to obtain a unitless Benefit-Cost Ratio (BCR).

$$BCR = \sum_{t=0}^{n} \frac{B_t}{(1+r)^t} \Bigg/ \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \qquad \text{[equation 1]}$$

Net Present Value (NPV) analysis uses the same terms to determine the dollar difference between the present value of cash inflows and outflows over the specified period. NPV is used to analyze the profitability of a projected investment and to compare the rates of return of alternative projects.

$$NPV = \sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+r)^t} \qquad \text{[equation 2]}$$

In both equations 1 and 2, B_t is the value of benefits in year t, C_t is the value of costs in year t, n is the life of project (or planning horizon) and r is the specified discount rate (time value of money).

NPV ≥ 0 (the sum of discounted future returns is equal to or exceed the sum of discounted future costs) indicates that the project is economically feasible. NPV is considered superior to other metrics of economic gains from rangeland improvement practices because it accounts for the time value of money and provides a dollar value for the investment (Workman 1986). By contrast, BCR analysis provides a simple ratio of the present value of future benefits and costs, and BCR ≥ 1 implies economic feasibility.

Given that woody plant encroachment is problematic for the provision of high-quality water in the Barton Springs segment of the Edwards Aquifer, land managers need to evaluate alternative woody plant control options. Figure B1 illustrates the tradeoffs.

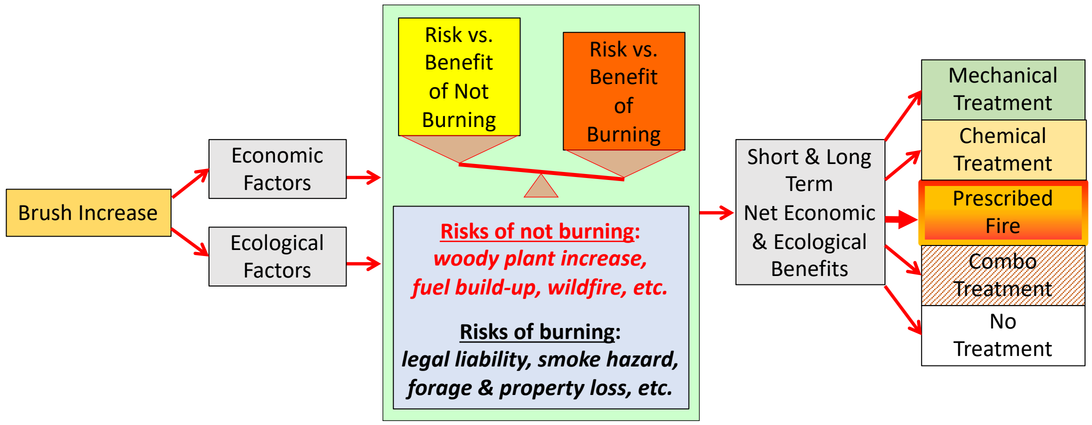

Figure A3.1. Conceptual framework for deciding to burn or not burn woody plants versus using other woody plant treatments (Toledo et al. 2012)

Assessment Approach

Eight steps would be required to conduct a comprehensive BCA and/or PNV for the Water Quality Protection Lands as follows (modification of method used by Stafford et al. 2018):

1. Map current and projected woody plant encroachment under different climate scenarios in each WQPL unit.
2. Model current and future water loss in each WQPL unit due to woody plant encroachment and future water gains resulting from woody plant control.
3. Identify and obtain values for additional ecosystem services (e.g., wildlife habitat provision, biodiversity enhancement, flood mitigation, etc.) in each WQPL unit that are affected by woody plant encroachment and control.
4. Identify the most feasible woody plant control treatments (per figure A3.1) and the estimated costs per acre of each treatment based on the conditions in each of the four cover types (Savanna Grassland, Interface Savanna, Savanna Woodland, and Warbler Woodland) in each WQPL unit (see Van Liew et al. 2012).
5. Rank each cover types in each WQPL unit by highest return on investments, i.e., by greatest water yield per unit cost.
6. Build discounted timeline for priority cover types in each WQPL unit, including initial restoration and subsequent maintenance costs for the vegetation condition required for optimal water yield.
7. Conduct BCA and PNV assessments based on the range of future direct and indirect benefits (water yield and other ecosystem services, respectively) and restoration and maintenance costs for each WQPL unit.
8. Compare cost per cubic meter, expressed as Unit Reference Value (URV) and potential yield gains of restoration program to alternative water supply options.

Data Acquisition

To achieve the objective of comparing the economic effectiveness of woody plant treatment with other methods for water generation, relevant information for each of the four cover types in each WQPL unit need to be obtained. Since substantial amounts of the required data may not be published, meetings with WQPL staff may be necessary to obtain primary information about each plant cover type. Information to be obtained during these meetings and during follow-up communications with the Natural Resources Conservation Services (NRCS) and Texas AgriLife Extension personnel include descriptions of various bush treatments, including currently applied treatments and other alternatives, and the costs of applying these treatments. Herbaceous forage response data following brush treatments will also be required and obtained from the WQPL staff. Based on this information, brush treatments evaluations should include the initial treatment and a series of follow-up treatments at specified intervals over a 20-year planning horizon. Brush cover can be categorized as heavy (>50% cover), moderate (25-50% cover) or light (10-25%).

In conducting the economic analysis, two parameters will need to be determined. (1) The planning horizon for assessing the woody plant retreatment effects; 20 years is a commonly used planning period – a range of planning horizons including 10, 20 and 30 years could be included to capture the anticipated 10 year-period of persistent penetrability effects, and the 20–30-year generational time span. (2) The discount rate for assessing the PNV of future benefits and costs will have to be determined; 6% is a frequently used discount rate (it is approximately two times the inflation rate and ~1.5 times the current Treasury bill rate); however, a lower discount rate might be warranted because the woody plant removal costs occur at the start of the project period (i.e., have a high PNV), whereas the per annum public benefits of providing high quality water accrue throughout the planning horizons (i.e., their PNV diminishes).

Valuation of Benefits

Additional water production: Benefits associated with the removal of encroaching woody plant will consist primarily of the extra water produced. Demand for water is likely to increase over time as water demand increased due to continued population growth in and around the City of Austin, thereby driving up the cost of water to consumers. Data for the current and projected future water prices should be available from the City of Austin's Water and Wastewater Utility.

Additional ecosystem services: Valuing the benefits of other ecosystem services that are enhanced by the removal of encroaching woody plants is more challenging because most ecosystem services represent dispersed public goods for which markets prices do not exist. Indirect evaluation methods are often used to derive a value for such ecosystem services. These methods include proxy market-based methods (production function values, replacement cost or cost saving values); revealed preference methods (hedonic value, travel cost); and stated preference methods (contingent valuation; and choice experiment/conjoint analysis). The most appropriate valuation method will depend on the types of ecosystem services that will be enhanced. For simplicity, the benefit transfer method has been widely used; this involves applying the average of numerous estimated values of ecosystem services from a broad range of locations. The most cited application of this method is Costanza et al (1987), who estimated the global value of ecosystem services. Although this method has been criticized because it applies average instead of marginal values to ecosystem services that vary in scarcity and therefore value, it has nevertheless been widely used together with sensitivity analyses to estimate the robustness of the derived values (e.g., Kreuter et al. 2001; Yi et al. 2017; Yi et al. 2019). Another approach to estimate the value of an improved wetland/riparian area could be determining the cost of constructing a water purification plant that would produce the same additional water quality as that produced by the improved functionality of the wetland or riparian area. In addition, the hedonic value of open space enhancement could be determined by the calculating the extra price of homes located near the WQPL properties that protect such open space.

Valuation of costs

The first determination will be the extent to which alternative woody plant treatments can be feasibly applied on the WQPL (Section 4.6). Severe prescribed fire is the most effective for quickly reducing the cover of encroaching woody plants, especially the pervasive Ashe juniper (*Juniperus ashei*). However, the application of this treatment type may not be ubiquitously practical or socially feasible. Mechanical or herbicide treatments may be necessary in some locations but the economic feasibility of those treatment types, especially at large scale, has been questioned (Van Liew et al. 2012). Previous research identified alternate treatment for Ashe juniper, a non-sprouting species, included ground-level cutting and stacking for moderate cover and mechanical grubbing and stacking plus grubbing alone for heavy cover (Van Liew et al. 2012).

Once the spatial potential of each of these treatment types has been determined for each WQPL unit, then the following cost items will need to be determined for each treatment type: labor, equipment, supplies, sundries. Standard costs are available for numerous woody plant treatment types through WQPL staff and the NRCS Environment Quality Incentive Enhancement Program.

Timing and type of follow up treatments to ensure longevity of the initial woody plant treatments will also need to be determined. The cost of each of these follow up treatments will need to be included in the NPV assessment in the year they occur. The costs for each follow up treatment will be similar to the initial treatment, although local variations may occur. One additional follow up treatment that is considered in this management plan is the use of goats to maintain browsing pressure on woody plants. The contract cost for introducing goats to browse woody plants will need to be included in the NPV calculation in the years when such browsing is anticipated.

Conclusion

Conducting an economic benefit cost analysis (NPV assessment) of the proposed woody plant control treatments is highly recommended to provide support for the public investment in the management of encroaching woody plants for the purpose of maximizing high-quality water yield in the Barton Springs segment of the Edwards Aquifer. The analysis recommended here would provide not only the direct benefit/cost value of reducing woody plants cover for water yield, but also the indirect benefits of the enhancement of other ecosystem services provide by the WQPL, including wildlife habitat provision, carbon sequestration and flood mitigation provided by open space protection by the WQPL.

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Appendix 5: Water Quality Protection Lands Climate Change Projections

Projected Climate Change in Central Texas

The Fourth National Climate Assessment (2018) provides a comprehensive overview of projected climate change in the United States. For the Southern Great Plains region (Kloesel et al. 2018) "climate change is expected to lead to an increase in both average temperatures and frequency, duration, and intensity of extreme heat." Mean annual temperature may increase by 4-8° F (2-4° C) by the end of the century. The number of days with high temperatures over 100° F (37.8 ° C) may increase by 30-60 days per year. Changes in mean annual precipitation (MAP) will likely be small, but variability will be higher. Extreme winter cold is projected to decrease, however polar vortex disruption associated with climate change may be poorly represented in climate models (Cohen et al. 2021). It is anticipated that the frequency and intensity of heavy precipitation will increase with a commensurate increase in flash flooding. In addition, the frequency, duration, and intensity of drought will increase. Increasing drought will be associated with drying soils due to higher evapotranspiration. These projections are largely in agreement with a recent report by Nielsen-Gammon et al. (2021) who examined historic trends in extreme weather in Texas and projected future trends. They did point out in this report that because of a warming and drying climate, Texas would be at risk of more frequent and extreme wildfires.

Climate and the Savanna Biome

With mean annual precipitation of 880 mm, strong seasonality including annual drought, and historical fire frequencies of 2 to 4 yr, WQPL falls within the global environmental range of savannas (Lehmann et al 2011; Novak et al. 2021). Based on climate projections for the Austin region, we do not expect WQPL to shift outside of the environmental constraints that form savannas. If anything, climate change will strengthen the climate-vegetation-fire relationships that have produced and stabilized savannas in the region for thousands, and likely millions, of years (Stromberg 2011).

Across the global tropics and subtropics, fire-dependent savannas occupy a broad range in mean annual precipitation from 250 mm to 2500 mm (Lehmann et al. 2011). Within these precipitation ranges, seasonality is important to limiting tree dominance and curing grassy fuels that promote flammability. Where seasonality is weak and precipitation is high (>1000 mm MAP), very frequent fire is critically important to the existence of savannas (Staver et al. 2011). In seasonally dry regions with lower precipitation (250-1000 mm MAP), such as the Southern Great Plains, the frequency of fire needed to maintain savannas is thought to decline with aridity. Models of historical (pre-Columbian) fire frequency suggest fires burned once every 2 to 8 yr in the humid and semi-arid regions of east and central Texas, whereas fire was less frequent, every 20 to 30 years, in more arid west Texas (Guyette et al. 2012).

Savannas have been the predominant ecosystems of Central Texas throughout most of the Holocene Epoch (past 18,000 years, since the last glacial maximum) and have occurred in the region in some form since at least the beginning of the Pleistocene Epoch (2.6 million years ago). Paleoecological studies of pollen in sediments from Hershop Bog near Ottine, TX (Larson et al. 1972), pollen records from Freisenhahn Cave (Hall and Valastro 1995), and pollen, phytoliths, and charcoal from Hall's Cave in Kerr County, TX (Cordova and Johnson 2019) provided a picture of climate, vegetation, and fire since the last glacial maximum. These studies suggest that savannas—composed of many of the same grass taxa found today on WQPL—were present even during the last glacial maximum, when temperate forest species reached their peak dominance. During the Holocene, climate fluctuations and burning by Native Americans contributed to shifts in species compositions that are within the range of savanna community variation that we see today. Although we do not have paleoecological records that go back further, studies of savanna plant endemism and glacial climate refugia throughout the North American coastal plain suggest that the savannas found today on WQPL occurred in some form in the region throughout the Pleistocene (Noss 2012).

Undoubtedly, temperatures during the next century will be higher than at any time in the Holocene. Indeed, a recently published model of future urban climate analogs, under the worst-case scenarios of CO_2 emissions, suggests that the climate of Austin in the late 21st century is approximated by Nuevo Laredo, 200 miles to the south near the Mexican border (Fitzpatrick and Dunn, 2019). It is important to recognize that prior to European land-management practices that caused widespread woody encroachment, the native ecosystems of south Texas were savannas (Archer et al. 2001). In sum, while Austin's climate will warm considerably, we can expect the ecosystems of the WQPL to remain in the climate range typical of savannas.

Climate resilience from savannas and prescribed fire, not forests and tree planting

Public concern over climate change has influenced policymakers to pursue carbon neutrality. Approaches to carbon neutrality, or net-zero carbon emissions, include reduced carbon emissions, increased carbon sequestration, or both. The City of Austin's *Climate Equity Plan* calls for net-zero community-wide greenhouse gas emissions by 2040 (CITE). This plan may affect WQPL because the Natural Systems section of the *Climate Equity Plan* calls for City-owned lands to be managed to achieve neutral or negative carbon emissions by 2030.

It is a common misperception that trees and forests offer the best, cheapest, and most reliable carbon sequestration to combat climate change and achieve net-zero emissions (Veldman et al. 2019). While it is true that in certain environments forests do offer a valuable service toward carbon storage, in seasonally dry subtropical regions like Central Texas, savannas offer a broad suite of ecosystem services that are important for climate resilience. From a carbon sequestration standpoint, a growing number of studies in drought and fire prone environments conclude that savannas are more secure carbon sinks than forests (e.g., Dass et al. 2018). Savannas store most of their carbon in soil organic matter and underground organs (roots and rhizomes, Grace et al. 2006), where it is safe from fires. Further, the underground storage organs of savanna plants enable them to survive fire and drought by resprouting and rapidly recovering carbon that was temporarily lost from aboveground organs. By contrast the carbon sequestered by trees is vulnerable to drought and fire, making trees a poor long-term carbon sink in savanna regions (Veldman et al. 2015, Dass et al. 2018). A further carbon benefit from savannas comes from the charcoal produced during prescribed fires that becomes incorporated into the soil (Bowring et al. 2022). By contrast, tree planting and fire exclusion in savannas can deplete soil organic matter, depending on soil type and water availability (Jackson et al. 2002).

Atmospheric carbon sequestration should be just one aspect of climate change mitigation to consider in management of WQPL: management for climate resilience needs to ensure the provisioning of water, reduce wildfire risk, and manage ecosystem energy balance (albedo). The potential contribution of ecosystems of WQPL to sequester additional carbon toward a net-zero strategy will be modest at best, with McCaw (2012) estimating that sequestration in Austin's publicly owned lands ecosystems captures only 1.6% of Travis County 2007-level emissions. Clearly the more important climate resilience benefit of WQPL will be to ensure that vegetation management safeguards water recharge. Because woody encroachment can reduce water recharge in seasonally dry and drought-prone regions (Jackson et al. 2005), restoration and conservation of WQPL savannas will be the best approach to secure water resources, even if it does not maximize near-term carbon sequestration. Dense juniper woodlands pose an extreme fire risk relative to savannas. With climate change producing higher temperatures and more severe droughts, wildfires are inevitable. Prescribed fire management in WQPL savannas can help reduce the intensity and danger of these future fires relative to what we would expect with widespread juniper encroachment. Savannas may also offer a climate cooling effect, relative to juniper woodlands, due to their effect on ecosystem energy balance. Savannas have high albedo, meaning that they reflect far more sunlight back to space compared to dark-colored evergreen trees. When trees absorb sunlight (short-wave radiation) that energy is re-emitted as long-wave (thermal) radiation. This thermal radiation is the heat that contributes to the greenhouse effect. In many regions of the world, including semi-arid ecosystems with low-cloud cover, the decrease in albedo from woody encroachment can negate the positive effect of sequestered carbon in shrubs and trees (Rotenburg and Yakir 2010). Management for highly reflective savannas likely offers the best combination of long-term carbon sequestration and ecosystem energy balance.

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Appendix 6: Water Quality Protection Lands Equitable Community Engagement

Guiding principles

As Central Texas grows in population, opportunities to protect new conservation lands that safeguard our limited groundwater grow scarce. This reality requires Water Quality Protection Lands staff to increase efforts to engage local communities in the continued protection and restoration of the land.

Community engagement centers on personal experiences aimed at enhancing public understanding and appreciation that:

- Protecting vast, contiguous wildlands helps to safeguard groundwater resources
- Active land management is key to conservation
- Prescribed fire is an essential tool for native Texas grassland savanna
- Restoration strategies adapt according to updates gained through scientific studies
- Public appreciation of public land will aid in its perpetual protection

Strategies

Six major strategies for outreach and engagement on the Water Quality Protection Lands:

1. **Volunteer opportunities**
   - Restoration workdays
   - Leadership positions that allow volunteers to lead workdays and hikes
   - Development of guided hikes
   - Contribution to scientific studies (live fuel moisture monitoring, vegetation transects, etc.)
   - Native plant propagation, preparation, and identification
   - Karst feature identification and restoration
2. **Guided interpretive hikes**
   - Easy and family-focused walks
   - Intermediate hikes
   - Full-day hikes
3. **Online outreach**
   - Monthly newsletter
   - Weekly social media posts
   - Webinar series
   - Library of related videos and storymap
   - Interaction with near peer organizations on social media
4. **Public events**
   - Tabling at targeted public events
   - Large festivals related to conservation, groundwater, grassland savanna
   - Relationships with nonprofits focused on underserved populations and communities of color
5. **Targeted experiences for teachers and students**
   - Funding and organization of local teacher trainings that provide continuing education credits – Groundwater to the Gulf, Project Wild
   - Beginning in 2023, we hope to bring 1-4 classes from Hays County schools to the WQPL yearly
6. **Cultivation of grassland savanna conservation community**
   - nERD: (notorious) Ecological Restoration Discussion
   - Texas Society for Ecological Restoration
   - Grassland Collective field trips

Plans for continued growth

In 2018, we celebrated 20 of the WQPL. We carved out extra staff time to get to know neighbors, community leaders, and stakeholders in Hays County and to better understand community perceptions about the WQPL. This focused, diligent effort yielded stronger relationships and a major realization: *communities surrounding the WQPL liked the idea – but did not realize it exists.*

After the 20th anniversary, staff time (for community engagement, WQPL biologists and program manager) necessarily shifted back to regular duties. We were unable to dedicate the same amount of effort into building relationships and meaningful ties through participation in community events, visits to libraries and schools and coffee shops, and conversations with elected officials. We focused our limited efforts on growing volunteer workdays aimed at active land restoration.

Thanks to a concerted, coordinated effort by staff, we increased the number of these events over the past several years. We began tracking participation in volunteer workdays as well as contributions to monitoring for seed ripeness to direct workday planning, collecting live fuel moisture samples that support our understanding of fire behavior and risk, and leading guided hikes for the public in 2017.

- 0-4 workdays/month in FY17 (32 events total)
- 1-5 workdays/month in FY18 (36 events total)
- 4-7 workdays/month in FY19 (55 events total)
- 5-6 workdays/month in FY20 until Covid-19 shut down
- 7-11 workdays/month in FY21 except in January, February, and August due to pandemic
- 8-12 workdays/month in FY22 (100+ events total)

One major change contributed to the increased community engagement – the shift of staff resources. In 2021, the division manager approved the community engagement team's request to shift the volunteer coordinator's efforts to focus more on building community support for, and participation in, WQPL volunteer workdays. With the addition of about 80% of the volunteer coordinator's time devoted to community engagement on the WQPL and using the remaining 20% of time to support other staff to continue Balcones Canyonlands Preserve (BCP) outreach, we learned that much more WQPL growth was possible. Even with a cautious approach necessitated by the Covid-19 pandemic, volunteer engagement on the WQPL increased dramatically in number of workdays overall and in the number and diversity of volunteers. One major concern was that this shift might undermine the success of volunteer workdays on the BCP. To the contrary, BCP volunteer workdays and engagement grew also, thanks in part to continued administrative support from the community engagement team, and in larger part to the dedication of time by BCP staff.

Looking forward, the division manager has supported a similar shift of effort in the role of the community engagement coordinator beginning in 2023. This will provide opportunities to engage much more with neighbors, community organizations, and elected officials in support of the WQPL program while maintaining continued support for BCP programs.

Snapshots from social media

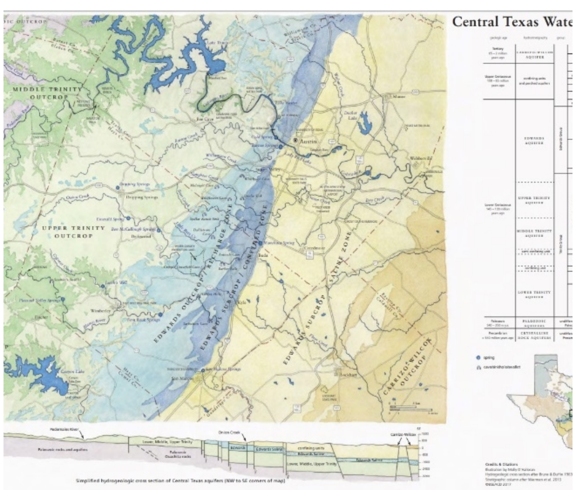
Happy Native Plants Week!

You can see more about Texas Native Plant Week at https://npsot.org/wp/ and some of the events happening this week like a Wild Plants of Texas Bioblitz, guest speakers and workshops, and more.

We have a couple of fun opportunities for you to get outside on the Water Quality Protection Lands this week!

Friday, September 14 from 9 am – 12 pm:
Join us to help harvest native seed and remove invasive plants.

Saturday, September 15 from 9 am – 12 pm:
Learn about Texas arthropods on our Insect Safari Hike – family and photographer friendly!



It's National Groundwater Awareness Week! Did you know that 98% percent of the available fresh water on Earth is groundwater?

Looking for more ways to help? Sign up to volunteer on Austin's Wildlands to restore conservation lands that help protect the Barton Springs segment of the Edwards Aquifer.

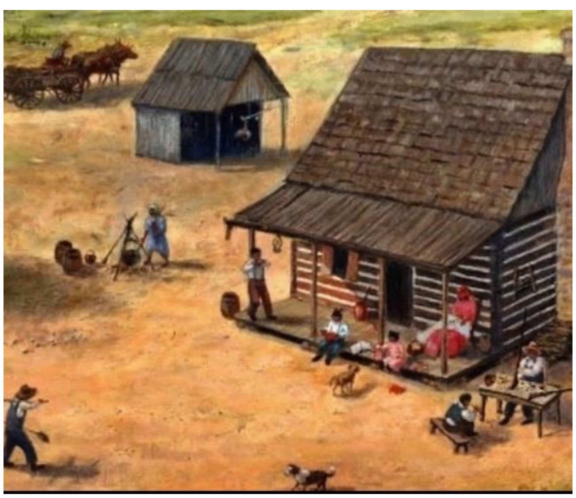
Sources: BSEACD and Groundwater Foundation

Will this hard work pay off? Yes! We recently re-visited an area treated with prescribed fire in the summer and then seeded by volunteers in the fall. This effort transformed the plant community, and we now see a wide variety of native species such as American germander (*Teucrium canadense*), Canada wild rye (*Elymus canadensis*), & plateau goldeneye (*Viguiera dentata*). This success and diversity couldn't be achieved without the help of our great volunteers!

Introducing Ella, who at only three weeks old is likely the youngest volunteer in our 20 year history! While we typically require volunteers to wear closed-toe shoes, we let Ella slide since she was on her best behavior (and in mom's arms).

Many thanks to Jessica and Ella for joining us to harvest native slimpod seed last Friday on the Water Quality Protection Lands. **#WQPL #ecologicalrestoration**

"Community-supported ecosystem restoration has the potential to help us thrive in more ways than one. It offers the opportunity to exercise, spend time in nature, contribute positively and actively to the betterment of the human and natural communities that we live in, and to see beyond cultural divisions and join others in the pursuit of a common goal." Read more about the challenges facing the iconic oak savannas of the Edwards Plateau in Water Quality Protection Land biologist Devin's blog and sign up to help volunteer!



"The Williams Farmstead Archeological Project is the most intensive archeological and historical investigation ever attempted for an African American-owned farmstead in Texas. The project has illuminated a comprehensive and detailed story of one African American family during its transition from slavery to freedom." Read more about the life and legacy of Sarah and Ransom Williams who built their farmstead on what is now part of the Water Quality Protection Lands.

It's National Take a Hike Day! Have you visited the Slaughter Creek Trail? This 5.25 mile hike, bike, and equestrian trail is in southwest Austin on the 657-acre Mary Gay Maxwell tract of the Water Quality Protection Lands. It is open to the public from dawn to dusk, but closed when conditions are too wet. Check @slaughtercrktrl on Facebook and Twitter to confirm that the trail is open before you head out. This trail is not open to dogs. 📷:@slaughtercrktrl

Maybe you're new to town, or maybe you've been thinking about connecting to your community in new ways, which we think is pretty great. Do you know someone who might enjoy getting involved exploring, volunteering, and learning on the Wildlands? Tag them below and find your role in wildland conservation and join our community of hikers and volunteers. #BenefitsBeyondWater #natureinthecity #atxvolunteers

The Water Quality Protection Lands manage grasslands and riparian ecosystems that support a healthy aquifer. Volunteers play a big role in ecological restoration through land stewardship activities, including collecting and spreading native seeds, removing invasive species, removing debris from caves, and many other activities.

#WaterQualityWednesday

There are many benefits of Austin Water's Wildlands! The Water Quality Protection Lands' main priority is to protect the source water that supplies Barton Springs. While protecting these lands and keeping them wild, we see additional positive effects and benefits including dark skies! The protected natural spaces of the Wildlands are truly dark at night - benefiting wildlife and humans, and contributing to breathtaking celestial views. Photo from @texasparkswildlife

#Regram from our friends at @elranchitocamp after a fun (and dirty) exploration of Whirlpool Cave! It was a blast learning and experiencing first hand how these caves play a role in water recharge - from the land surface, into our aquifer, and then flowing out at Barton Springs.

#wildlandsforwater #cavesoftexas #bartonsprings

Sylvia Pope, a Professional Geologist, studies recharge features, springs, and groundwater flow in karst settings throughout central Texas.

We are featuring her as one of our Women of the Wildlands on the Wildland Notes from the Field here: https://bit.ly/2EUdxYc

This year during the annual bird survey on the Water Quality Protection Lands (WQPL), more than 70 species of birds were documented on a single 460-acre tract! By protecting large tracts of land, with a variety of habitats, the WQPL offers a place for many species to thrive. Groundwater conservation brings biodiversity too!

#WildlandsForWater

Barton Springs is free all day starting today through February! Enjoy!

If you're looking for ways to support the Springs, come on out to volunteer on the Water Quality Protection Lands to help protect the source water that feeds it. Sign up at austintexas.gov/wildlandevents.

"The Water Quality Protection Lands (WQPL), created in 1998, safeguard groundwater that emerges at Barton Springs through the conservation and restoration of large, connected natural areas."

Read more about the hydrogeology and land management of the WQPL in our latest Notes from the Field blog post here: https://bit.ly/WhatIsTheWQPL

Native trees, grasses, and wildflowers are a daily source of curiosity and beauty across the Wildlands for volunteers, hikers, and staff alike. Thank you to the organizers of #blackbotantistsweek for putting together yet another week filled with education, black joy and empowerment of black faces in outdoor spaces!

More Water Quality Protection Lands to come!

In last week's election, Austinites voted – and overwhelmingly approved - $72 million to purchase additional conservation lands. Thank you!

#wildlandsforwater #atx #bartonsprings

We still have some space for you and yours on our long hike this Sunday, September 30! This hike will explore our ~3,500 acre Onion Creek property near Driftwood.

Hikers will traverse grassland savanna managed with prescribed fire, and will learn about the importance of water recharge features along Onion Creek and their connections with Barton Springs!

@ATXCouncil approves an agreement with @WildflowerCtr

and @AustinWater

Wildland Conservation Division to coordinate prescribed burns, wildfire prevention and preparedness, and for assistance on possible fire incidents on 40,000 acres of Austin's conservation lands.

#atxgoodfire

Appendix 7: Wildfire Prevention Plan

Location of Work:

BCP: YES / NO

WQPL: YES / NO

Tract name(s): ______________________________

Nearest gate address: ______________________________

GPS Coordinates: ______________________________

Date(s): ______________________________

Type of work: ______________________________

____

____

____

____

Specifics of Work: ______________________________

____

____

____

____

Number of personnel:

____

Fire prevention/ suppression equipment on site: ______________________________

____

Fire prevention preparation: ______________________________

____

Fire department jurisdiction: ______________________________

Spotter: During active high fire danger periods a member of the work group will be designated as a spotter to observe and report potential wildfire ignitions. During hot work such as welding, or high-risk activities such as operation of vehicles or power equipment in heavy fuels the spotter will be dedicated only to that responsibility.

Name of designated spotter: ______________________________

Emergency contact: An emergency contact will be the designated point of contact who will be available in the event Wildland Conservation Division Management needs to contact a project team in the field.

Name of emergency contact: ______________________________

Best method of contact: # ______________________________

Personnel: ______________________________

____

Supervisor name(s): ______________________________

____

Supervisor phone(s):

____

____

Project Manager WCD: ______________________________

Project Manager WCD Phone: # ______________________________

In the event of a wildfire, DIAL 911 before notifying WCD staff.

If suppression efforts are successful, suspend project activities and notify project manager and:

WCD Fire Program: **Matt Lore (cell 347-276-3117), desk 512-972-1685)**

WQPL Manager: **Kevin Thuesen (cell 512-632-8064), desk 512-972-1666)**

BCP Manager: **Nico Hauwert (cell 512-695-4597), desk 512-972-1661)**

WCD Manager: **Matt Hollon (cell 512-740-0749), desk 512-972-1696)**

Appendix 8: Woody plant response to treatment on the Water Quality Protection Lands

Adaptive management, whereby land management decisions are informed via a continuous, iterative cycle of monitoring and analysis, has been a core component of the WQPL land management regime since this approach was proposed in the WQPL 2001 Recommended Land Management plan. Tables and plots on the following pages display the results of statistical analysis of woody plant response to management interventions and rest periods between 2006 and 2021. Woody plant cover is measured as the top layer of woody cover that overlaps 38 permanent 800 foot long transects. A total of 96 intervals, with a maximum duration of 3 years and a mean duration of 1.8 years, capture the effects of 39 rest periods during which no treatment is applied, 9 mixed brush shedding treatments where all non-oak woody plants <4" diameter at breast height (DBH) are masticated, 22 growing-season prescribed fires, 13 juniper thinning treatments, and 13 winter prescribed burns.

Linear regressions were used to predict treatment effects on 5 woody cover response variables: all woody species combined, live oak (*Quercus fusiformis)*, Ashe juniper (*Juniperus Ashei*), cedar elm (*Ulmus crassifolia*), and resprouting shrubs, which include Mountain laurel (*Sophora secundiflora*), Texas Persimmon (*Diospyros texana*), Yaupon holly (*Ilex vomitoria*), Texas kidneywood (*Eysenhardtia texana*), Agarita (*Mahonia trifoliata*), Gum bumelia (*Sideroxylon languinosa*), and Flameleaf sumac (*Rhus lanceolata*). The predictor variables evaluated for inclusion in each model are pre-treatment cover level (covariate), treatment type (categorical fixed-effect), the interaction between pre-treatment cover level and treatment type (interaction term), and transect site (random effect). Untransformed, log-transformed, and negative binomial distributions were considered for all models, as were multiple random effects matrix covariance structures. Model selection tables included below (Tables 16-20) show which models were selected on the basis of Akaike Information Criteria (AIC) values, and in one case, Kolmogorov-Smirnov p-value. Note that the random effect (transect site) was not included in the best model for any response variable, and that for all models considered, the log-likelihood value for the best fitting model that does include the random effect is identical or nearly so to that of the best fitting models, which do not include transect. In no case did the inclusion of the random effect result in a more than trivial difference (not reported) from the significance levels or predicted treatment effects reported in this appendix.

There are many practical implications that can be drawn from these analyses to inform land management. The effects of winter fire on total woody cover, live oak cover, Ashe Juniper cover, and cedar elm cover are not significantly different from rest. This analysis therefore predicts that prescribed fire applied in the winter is not an effective tool to reduce woody plant cover. The effect of any treatment on total woody cover is modest, predicted at less than 10%. Mixed brush shredding treatments and Juniper thinning treatments are specified to target 100% of non-oak woody plants less than 4" DBH (or in some cases up to 8" DBH for Ashe juniper), which demonstrates that, despite their apparent prevalence when viewed from eye-level, only about 10% of woody plant cover on the savanna grasslands of the WQPL are comprised of shrubs that are susceptible to the treatments analyzed here. The other 30% of woody plant cover is comprised of mature trees, which are not targeted by management interventions, though live oak, by far the most dominant woody plant on the WQPL which is otherwise relatively static, does show a small but significant negative response to growing season fire (-2.15%). The most significant treatment effect on cedar elm cover is an increase of 2.9% in response to juniper thinning, which partially offsets the woody canopy reduction effect of juniper thinning. Juniper increases by a predicted 5% per rest period, outstripping the predicted increase of total woody cover of 2.8% for a rest period, indicating that juniper is driving both woody encroachment into grasslands and is outcompeting other woody species at the top layer of canopy cover. Juniper is also the most responsive variable tested, with all treatments except winter fire inducing a significant negative response. Importantly, these models predict that no treatments studied here have the potential to reduce woody plant canopy cover near 15%, which is the estimated figure targeted in prior and current Recommended Land Management Plans to improve water yield in savanna grasslands. It is therefore appropriate and consistent with the observed and predicted effects of treatment to consider this a rough and long-term target, and that a gradual, sustained approach to canopy reduction is the only available method to decrease woody cover levels below intermediate ranges and thus improve water yield.

In the following data table, the probability values (p-values) of statistically significant items ($p<0.05$) items are bolded, whereas near significant items ($p<0.10$) ate italicized.

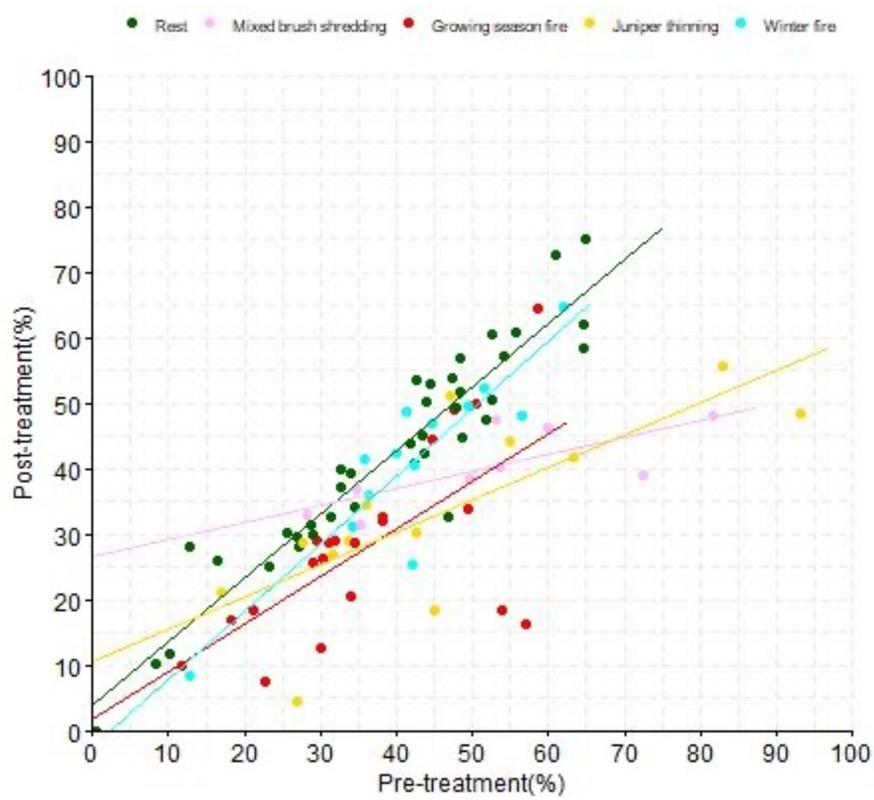


Figure A8.1. Linear regression of treatment effects on total woody plant cover

Table A8.2. Model summary table, response: post-treatment woody plant cover

Predictor	chisq (III)	df	p-value
pre-treatment woody cover	173.319	1	**<0.001**
treatment type	9.139	4	*0.058*
pre-treatment cover x treatment type (interaction)	28.025	4	**<0.001**

Table A8.2. Selected treatment slope comparisons (contrasts)

Predictor	z-statistic	p-value
shredding vs. rest	-4.161	**<0.001**
growing season fire vs. rest	-1.830	*0.067*
juniper thinning vs. rest	-3.843	**<0.001**
winter fire vs. rest	0.293	0.769

Table A8.3. Treatment effects on woody cover

Treatment type	predicted cover, starting from mean pre-treatment value (40.753%)	% change of mean pre-treatment value (40.753%)	% change out of 100% potential cover
rest	43.102%	6.960	2.805
mixed brush shredding	37.098%	-7.939	-3.199
growing season fire	31.098%	-22.767	-9.175
juniper thinning	30.512%	-24.284	-9.786
winter fire	39.200%	-2.723	-1.097

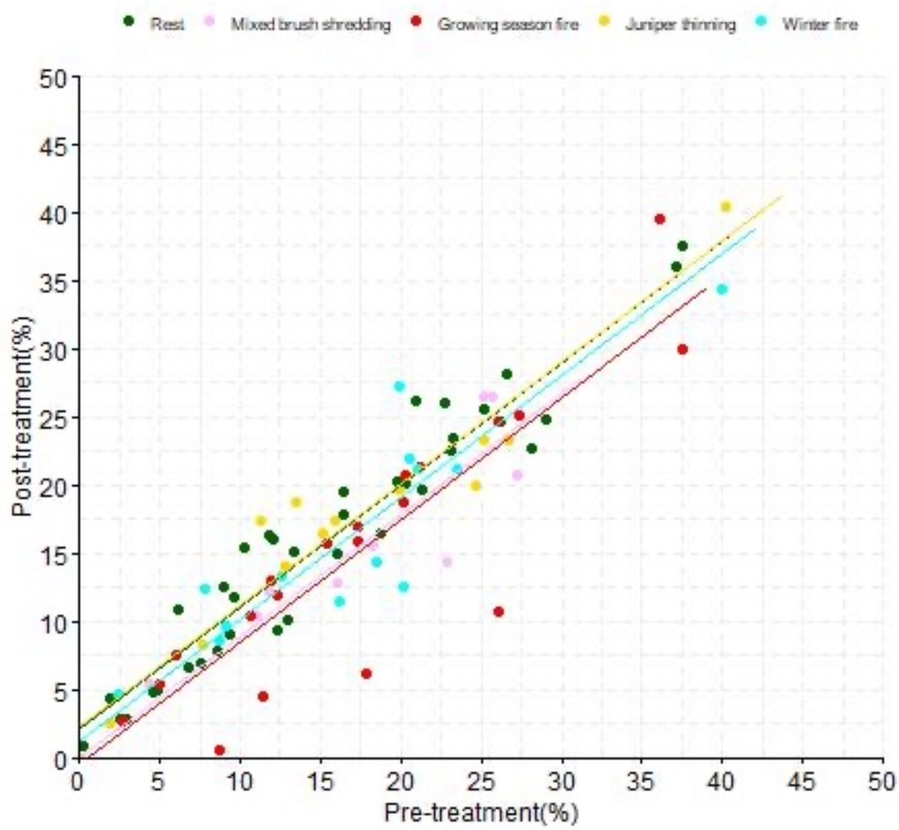


Figure A8.2. Linear regression of treatment effects on live oak cover

Table A8.4. Model summary response: post-treatment live oak cover

Predictor	chisq (III)	df	p-value
pre-treatment live oak cover	630.413	1	**<0.001**
treatment type	10.345	4	**0.035**

Table A8.5. Selected treatment intercept comparisons (contrasts)

Predictor	z-statistic	p-value
shredding vs. rest	-1.701	*0.089*
growing season fire vs. rest	-2.797	**0.005**
juniper thinning vs. rest	0.174	0.862
winter fire vs. rest	-0.788	0.431

Table A8.6. Treatment effects on live oak

Treatment type	% change out of 100% potential cover regardless of pre-treatment cover	Predicted cover, starting from mean pre-treatment value (16.090%)	% change of mean pretreatment cover (16.090%)
rest	0.368	16.459%	2.288
mixed brush shredding	-1.756	14.334%	-10.914
growing season fire	-2.148	13.943%	-13.349
juniper thinning	0.556	16.646%	3.454
winter fire	-0.483	15.608%	-2.999

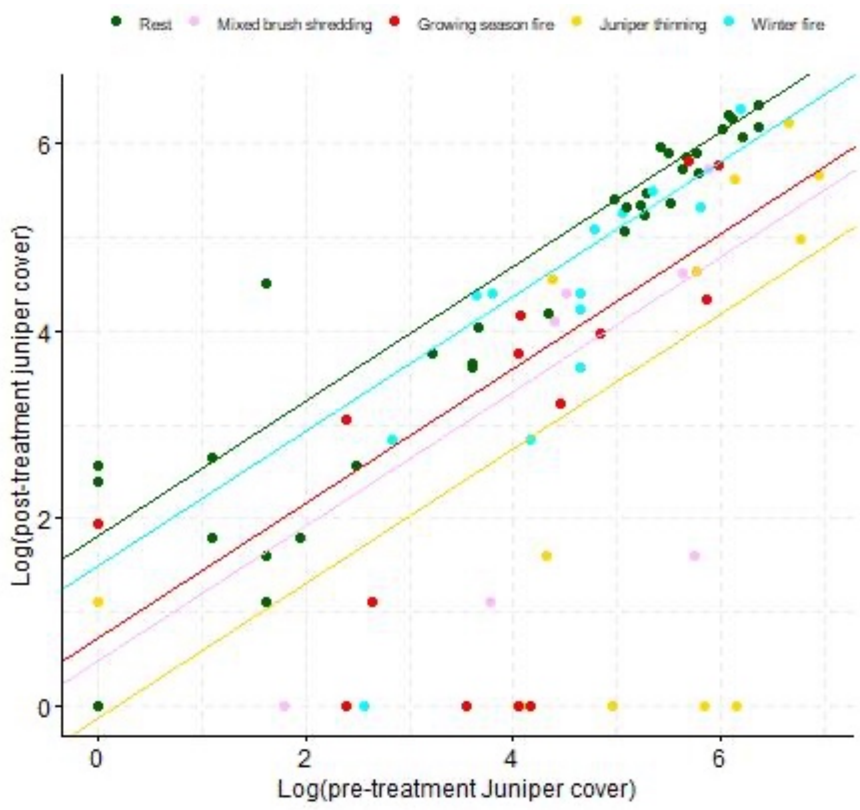


Figure A8.3: linear regression of treatment effects on Ashe juniper cover

Table A8.7. Model summary response: post-treatment Ashe juniper cover

Predictor	chisq(III)	df	p-value
log pre-treatment Ashe juniper cover	113.494	1	**<0.001**
treatment type	66.431	4	**<0.001**

Table A8.8. Selected treatment intercept comparisons (contrasts)

Predictor	z-statistic	p-value
shredding vs. rest	-3.926	**<0.001**
growing season fire vs. rest	-4.086	**<0.001**
juniper thinning vs. rest	-6.663	**<0.001**
winter fire vs. rest	-1.618	0.106

Table A8.9. Treatment effects on juniper cover

Treatment type	% change out of 100% potential cover regardless of pre-treatment cover	Predicted cover, starting from mean pre-treatment value (9.960%)	% change of mean pretreatment cover (9.960%)
rest	5.004	14.964%	50.239
mixed brush shredding	-6.0315	3.929%	-60.555
growing season fire	-4.940	5.020%	-49.597
juniper thinning	-7.826	2.134%	-78.573
winter fire	0.899	10.860%	9.024

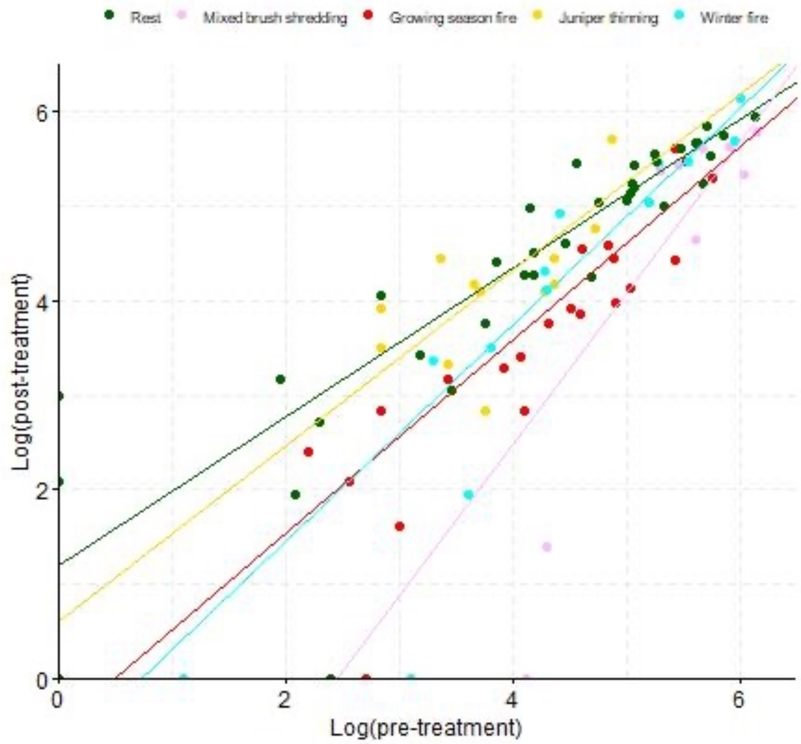


Figure A8.4: linear regression of treatment effects on resprouting shrub cover

Table A8.10. Model summary response: post-treatment cover

Predictor	chisq (III)	df	p-value
log pre-treatment resprouting shrub cover	146.496	1	**<0.001**
treatment type	19.703	4	**<0.001**
pre-treatment cover: treatment type (interaction)	15.768	4	**0.003**

Table A8.11. Selected treatment slope comparisons (contrasts)

Predictor	z-statistic	p-value
shredding vs. rest	3.260	**0.001**
growing season fire vs. rest	1.497	0.134
juniper thinning vs. rest	0.588	0.557
winter fire vs. rest	2.467	**0.014**

Table A8.12. Treatment effects on resprouting shrub cover

Treatment type	Predicted cover, starting from mean pre-treatment value (7.633%)	% change of mean pretreatment cover (7.633%)	% change out of 100% potential cover
rest	9.212%	20.686	1.579
mixed brush shredding	2.757%	-63.886	-4.877
growing season fire	5.197%	-31.925	-2.437
juniper thinning	10.149%	32.952	2.515
winter fire	6.775%	-11.241	-0.858

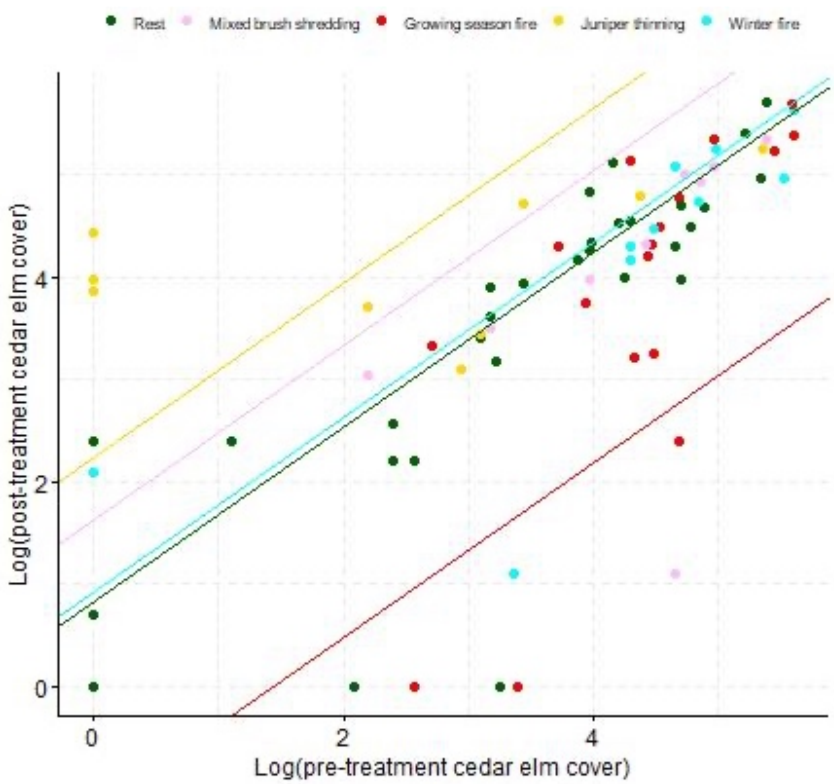


Figure A8.5. Linear regression of treatment effects on cedar elm cover

Table A8.13. Model summary response: post-treatment cedar elm cover

Predictor	chisq (III)	df	p-value
log pre-treatment cedar elm cover	72.469	1	**<0.001**
treatment type	12.289	4	**0.015**
pre-treatment cover: treatment type (interaction)	8.445	4	*0.077*

Table A8.14. Selected treatment intercept comparisons (contrasts)

Predictor	z-statistic	p-value
shredding vs. rest	0.520	0.603
growing season fire vs. rest	-1.926	*0.054*
juniper thinning vs. rest	2.237	**0.025**
winter fire vs. rest	0.114	0.909

Table A8.15. Treatment effects on cedar elm cover

Treatment type	% change out of 100% potential cover regardless of pre-treatment cover	Predicted cover, starting from mean pre-treatment value (3.92%)	% change of mean pretreatment cover
rest	0.981	4.902%	25.027
mixed brush shredding	0.330	4.251%	8.422
growing season fire	-1.043	2.877%	-26.608
juniper thinning	2.937	6.858%	74.919
winter fire	0.738	4.659%	18.830

Table A8.16. Model selection table for total woody plant canopy cover, normal distribution

Model terms	Additional random residual term	RE matrix covariance structure	KS test p-value	logLik	AICc	ΔAICc	df
*pre-treatment cover, treatment, pre-treatment cover x treatment	NA	NA	0.138	-579.178	1183.498	0.000	11
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogenous unstructured	0.133	-579.178	1186.114	2.616	12
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogenous comp. symmetry	0.133	-579.016	1188.472	4.974	13
pre-treatment cover, treatment	NA	NA	**0.033**	-587.937	1191.147	7.649	7
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogenous diagonal	0.209	-594.606	1216.971	33.473	12

Table A8.17. Model selection table for live oak canopy cover, normal distribution

Model terms	Additional random residual term	RE matrix covariance structure	KS test p-value	logLik	AICc	ΔAICc	df
*pre-treatment cover, treatment	NA	NA	0.669	-500.730	1016.733	0.000	7
pre-treatment cover, treatment,	transect	heterogenous comp. symmetry	0.569	-499.063	1018.219	1.486	9
pre-treatment cover, treatment,	transect	heterogenous unstructured	0.569	-500.730	1019.115	2.382	8
pre-treatment cover, treatment, pre-treatment cover x treatment	NA	NA	0.238	-504.894	1034.932	18.199	11
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogenous unstructured	0.230	-504.894	1037.548	20.815	12
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogenous comp. symmetry	0.230	-503.717	1037.873	21.140	13
pre-treatment cover, treatment, transect	NA	heterogenous diagonal	0.569	-515.698	1049.051	32.318	8
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogenous diagonal	0.384	-514.712	1057.184	40.451	12

Table A8.18. Model selection table for Ashe juniper canopy cover, negative binomial distribution

Model terms	Additional random residual term	RE matrix covariance structure	KS test p-value	logLik	AICc	ΔAICc	df
*pre-treatment cover, treatment	NA	NA	0.290	-420.883	857.038	0.000	7
pre-treatment cover, treatment, transect	transect	heterogenous unstructured	0.796	-420.883	859.421	2.382	8
pre-treatment cover, treatment, transect	transect	heterogenous diagonal	0.796	-420.883	859.421	2.382	8
pre-treatment cover, treatment, pre-treatment cover x treatment	NA	NA	0.685	-421.301	867.744	10.706	11
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogenous diagonal	0.623	-421.301	870.360	13.322	12
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogenous unstructured	0.623	-421.301	870.360	13.322	12

Table A8.19. Model selection table for resprouting shrub canopy cover, negative binomial distribution

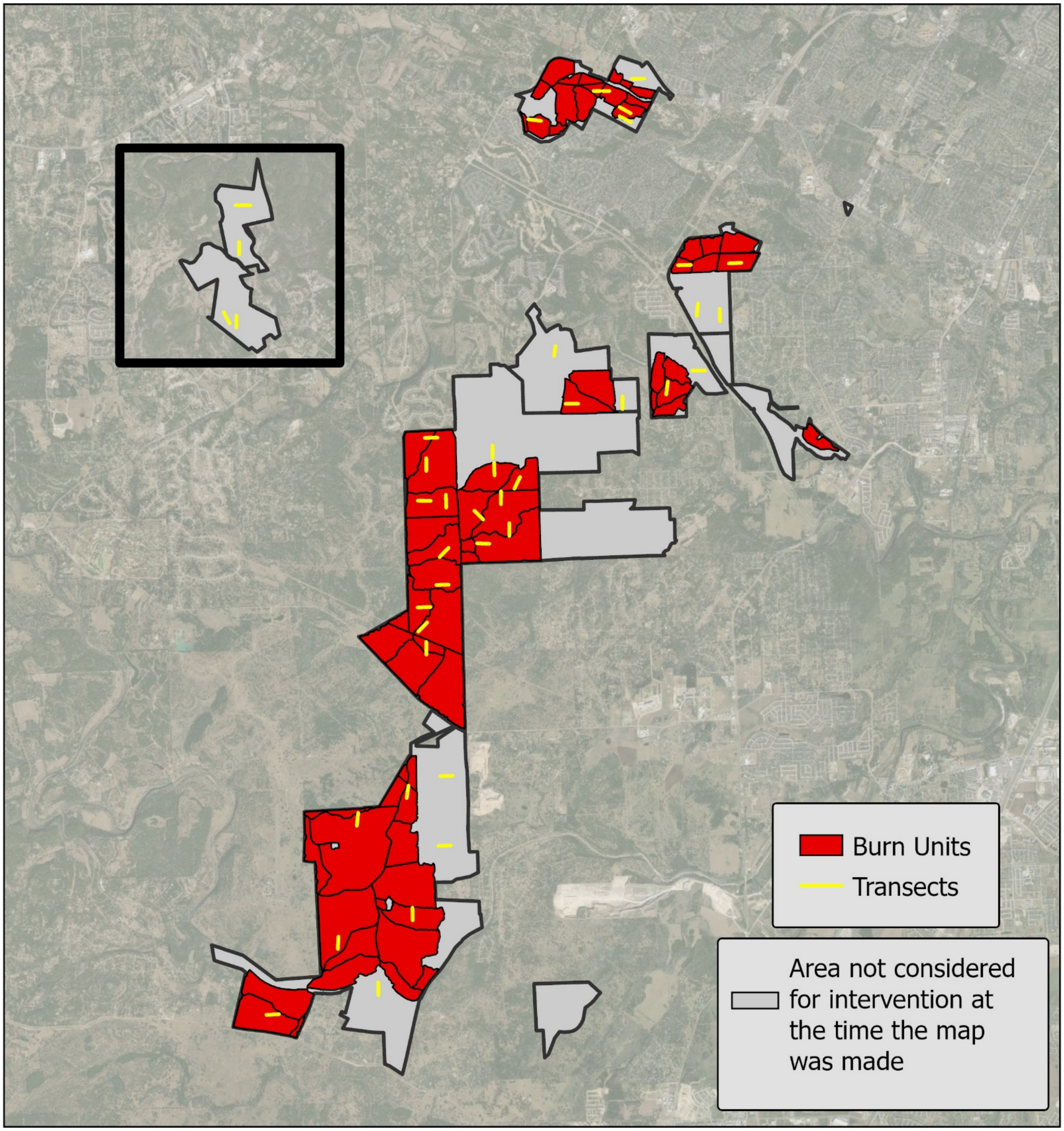
Model terms	Additional random residual term	RE matrix covariance structure	KS test p-value	logLik	AICc	ΔAICc	df
*pre-treatment cover, treatment, pre-treatment cover x treatment	NA	NA	0.937	-447.916	920.975	0.000	11
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogeneous diagonal	0.791	-447.296	922.351	1.376	12
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogeneous unstructured	0.791	-447.296	922.351	1.376	12
pre-treatment cover, treatment	NA	NA	0.948	-453.606	922.484	1.509	7

Table A8.20. Model selection table for cedar elm canopy cover, negative binomial distribution

Model terms	Additional random residual term	RE matrix covariance structure	KS test p-value	logLik	AICc	ΔAICc	df
pre-treatment cover, treatment	NA	NA	**0.015**	-392.175	799.622	0.000	7
*pre-treatment cover, treatment, pre-treatment cover x treatment	NA	NA	0.112	-390.396	805.935	6.312	11
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogenous diagonal	0.503	-390.396	808.551	8.929	12
pre-treatment cover, treatment, pre-treatment cover x treatment	transect	heterogenous unstructured	0.503	-390.396	808.551	8.929	12

WQPL Prescribed Burn Areas

Total Acres Burned - 11,113.3



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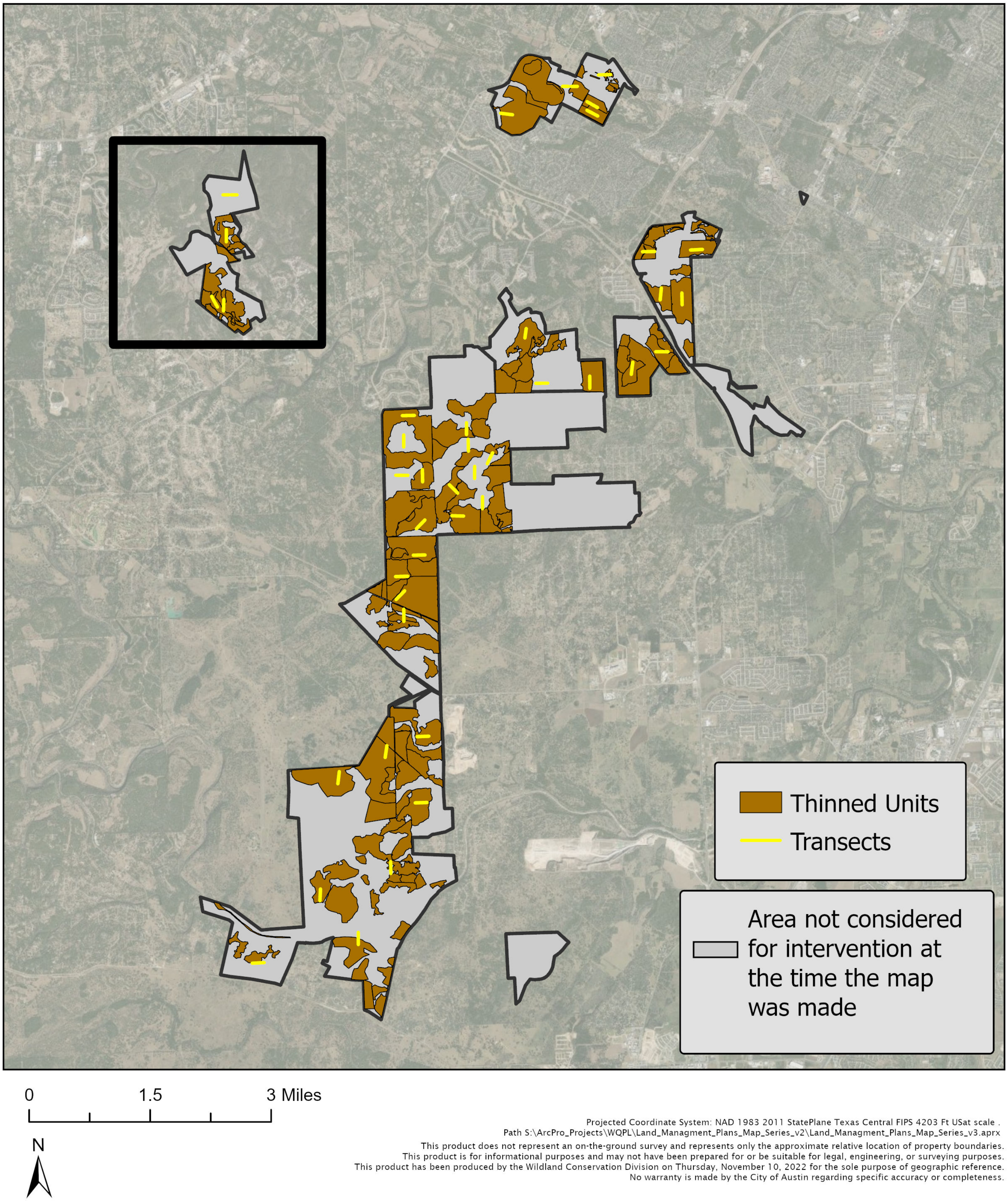
WQPL Thinned Areas

Total Acres Thinned - 5,888



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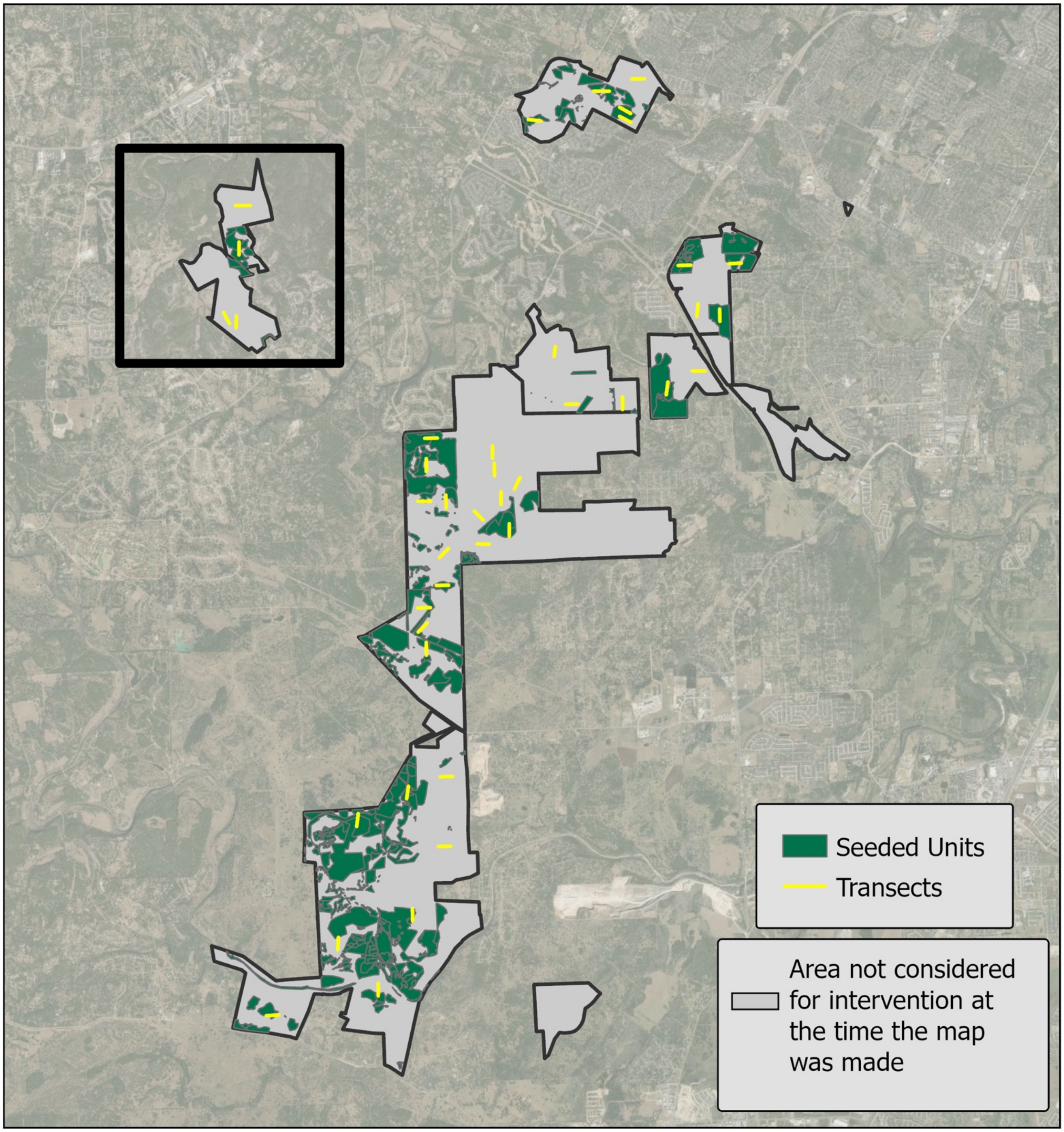
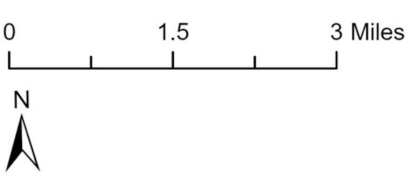
WQPL Seeded Areas

Total Acres Seeded - 2,735.8





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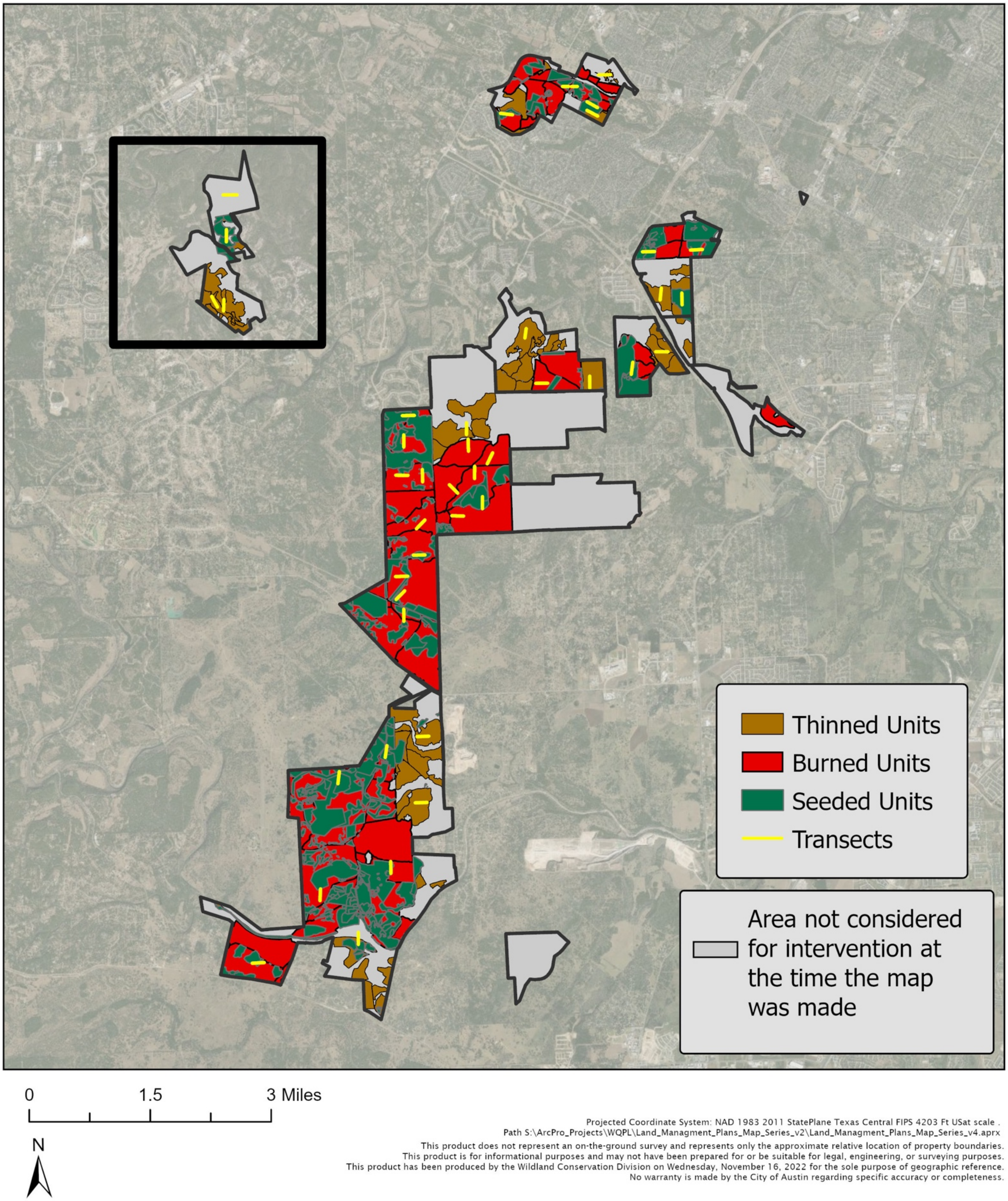
WQPL Total Treated Area

Total Acres Seeded, Burned, or Thinned - 19,737.1



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2022 Recommended Land Management for the Water Quality Protection Lands
Austin, Texas

Book 2
Figures

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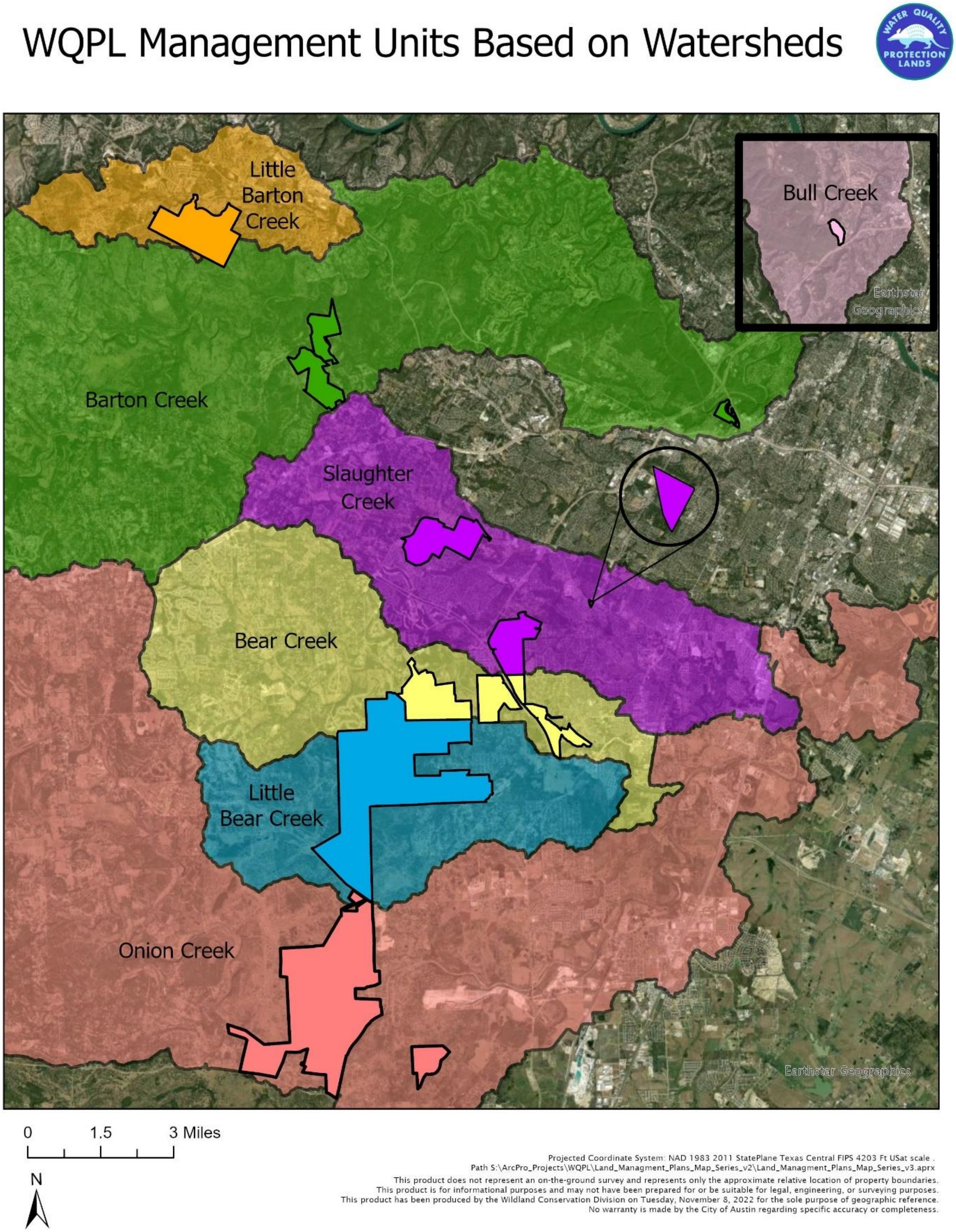

Figure 1: Water Quality Protection Lands management units located within watersheds.

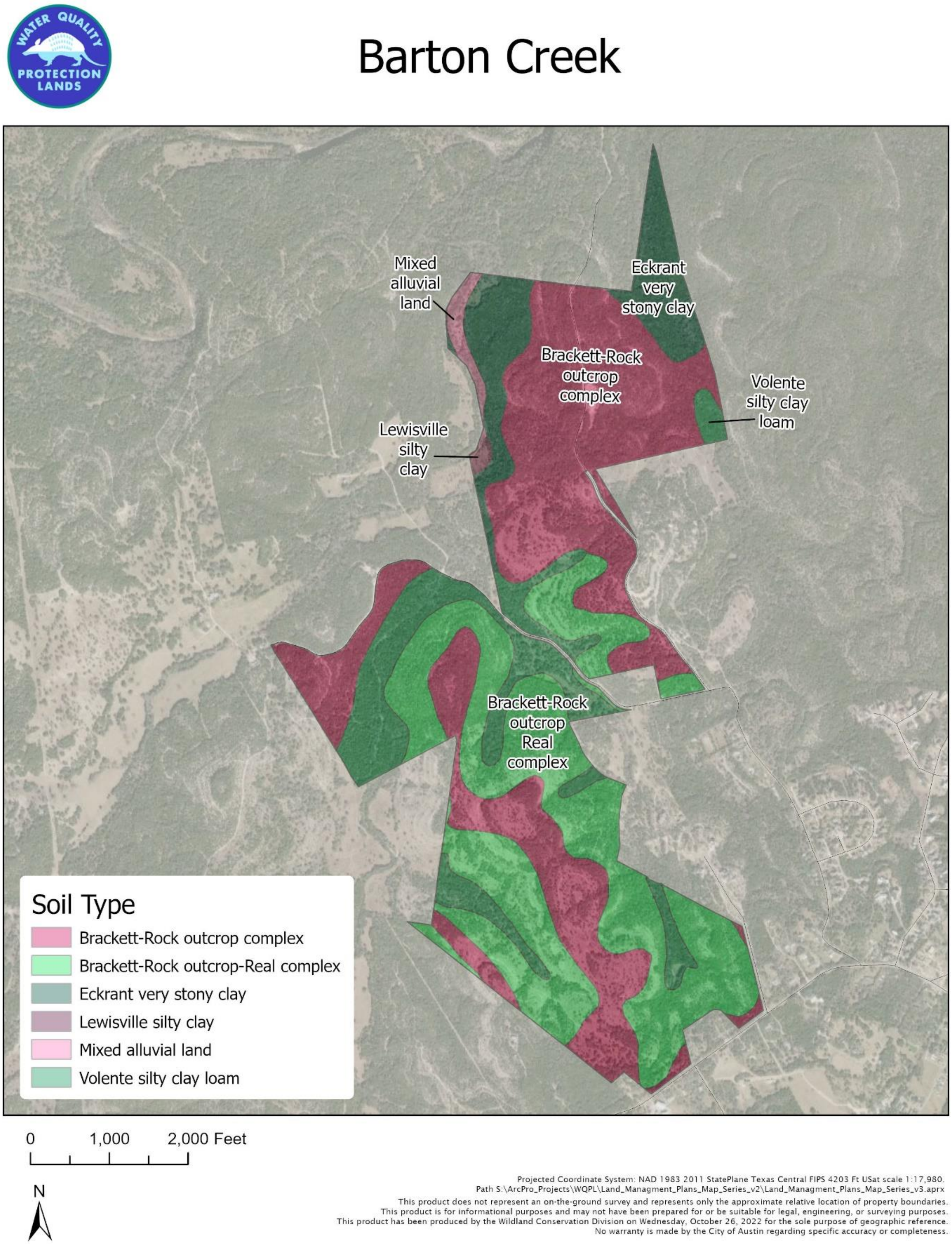

Figure 2: Soil types of Barton Creek management unit.

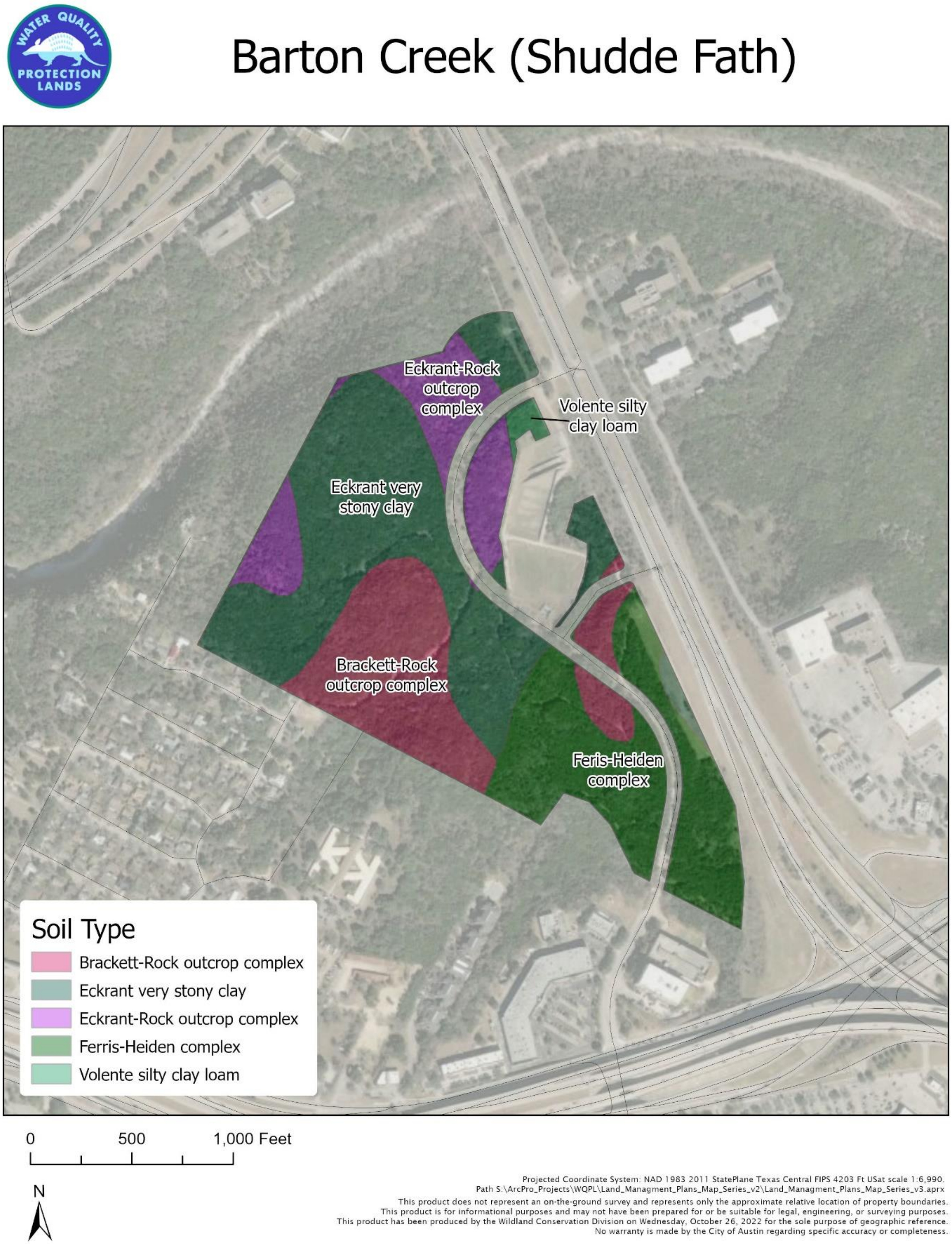

Figure 3: Soil types of Barton Creek (Shudde Fath) management unit.

Bear Creek (E)

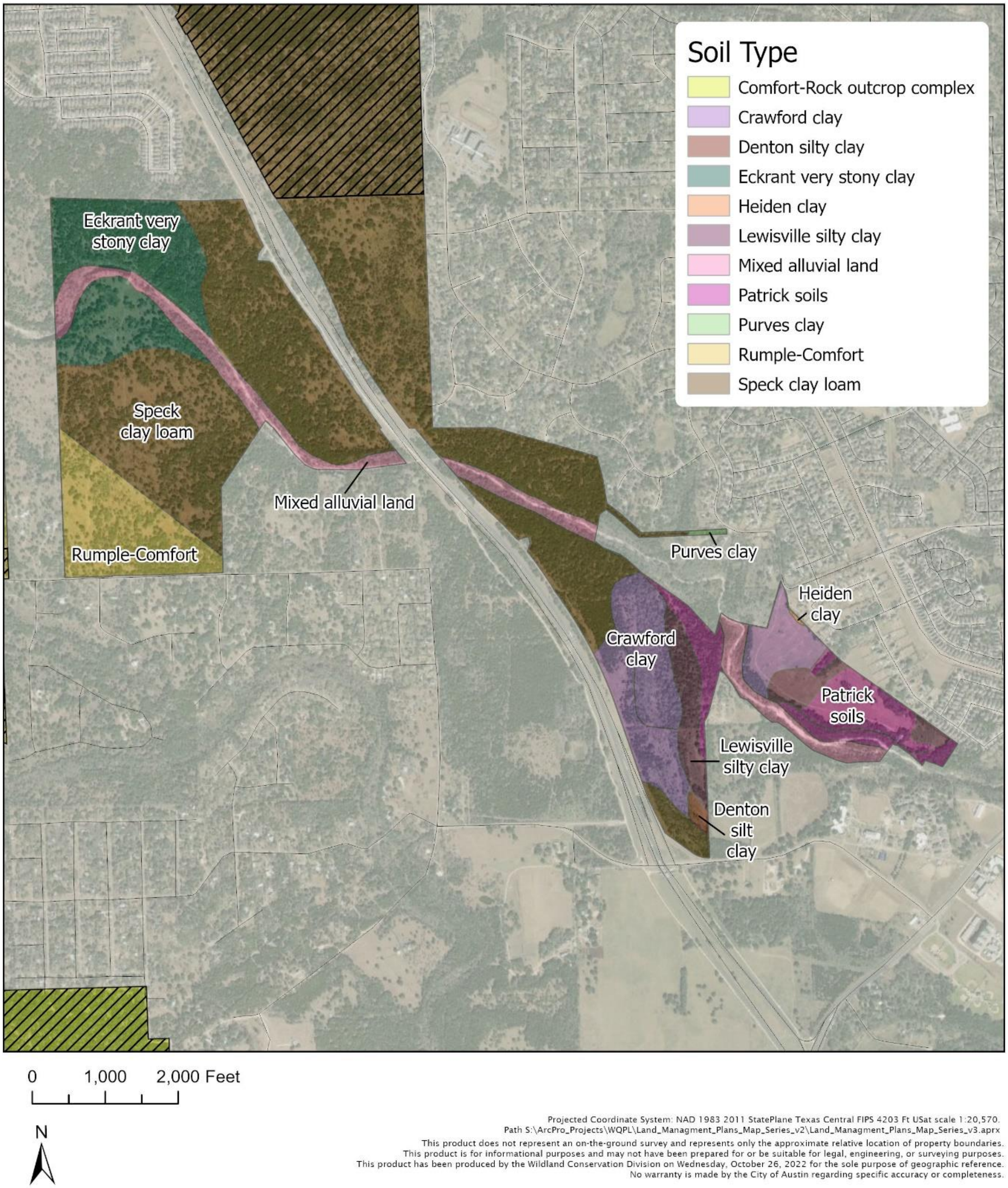

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Figure 4: Soil types of Bear Creek management unit (eastern side).

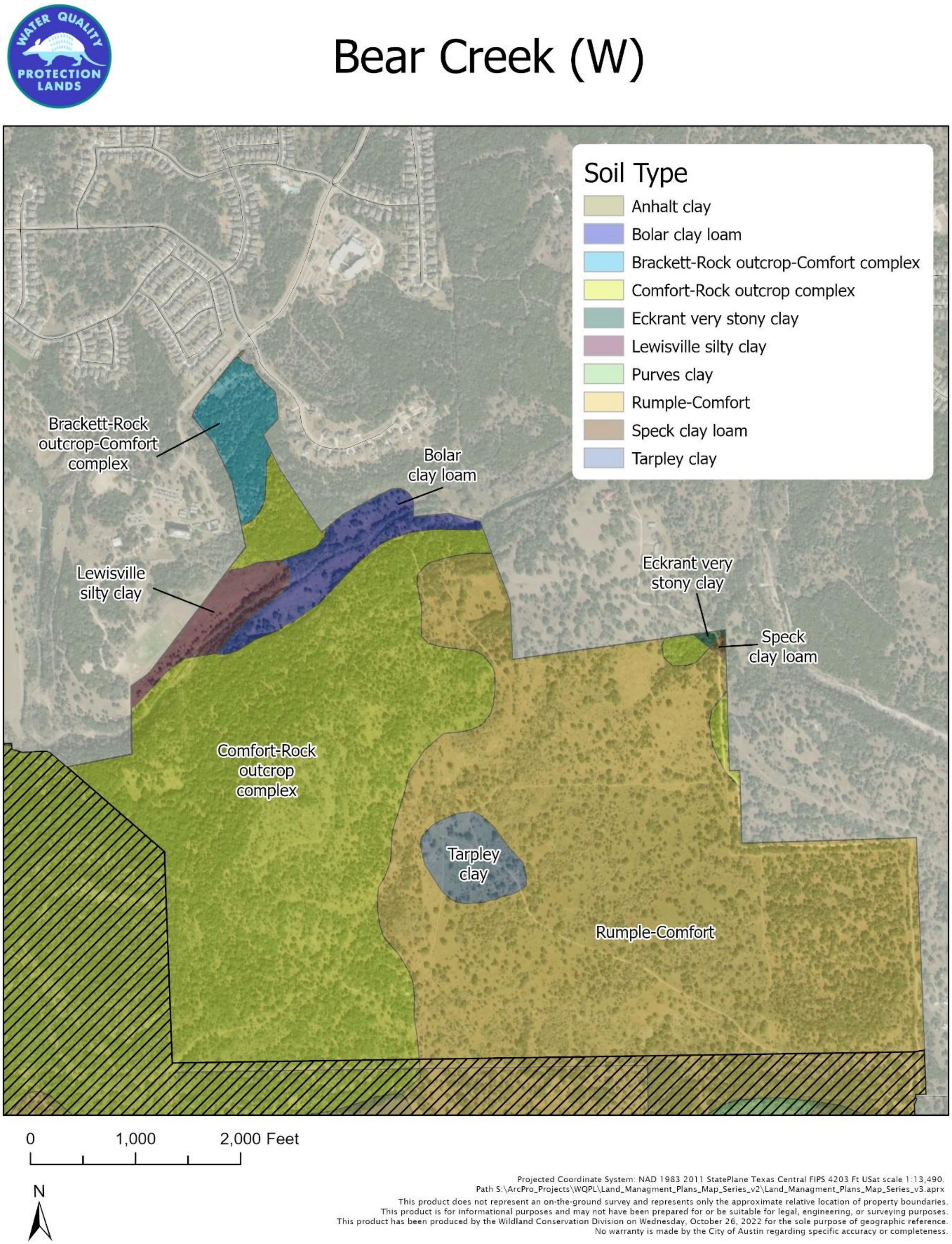

Figure 5: Soil types of Bear Creek management unit (western side).

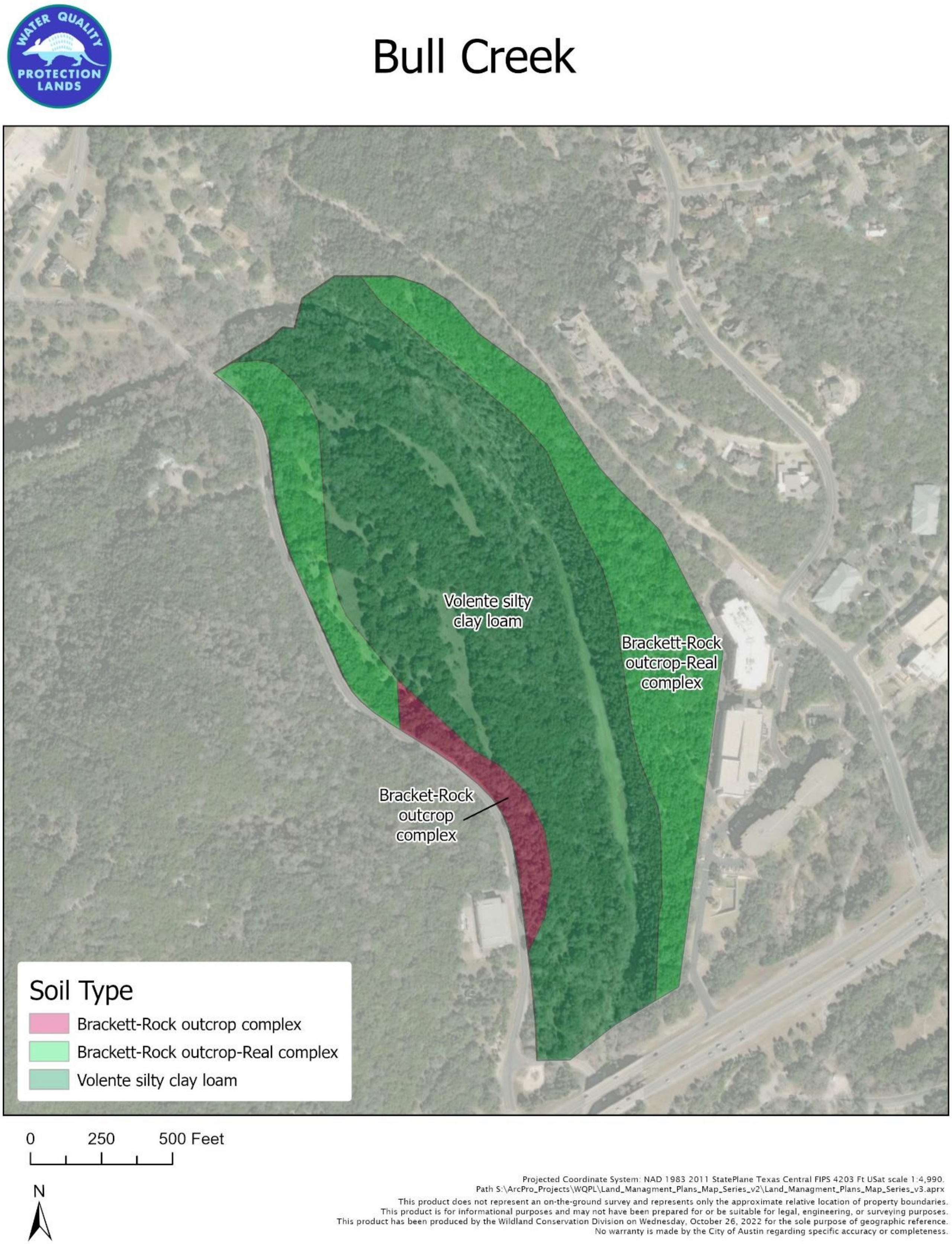

Figure 6: Soil types of Bull Creek management unit.

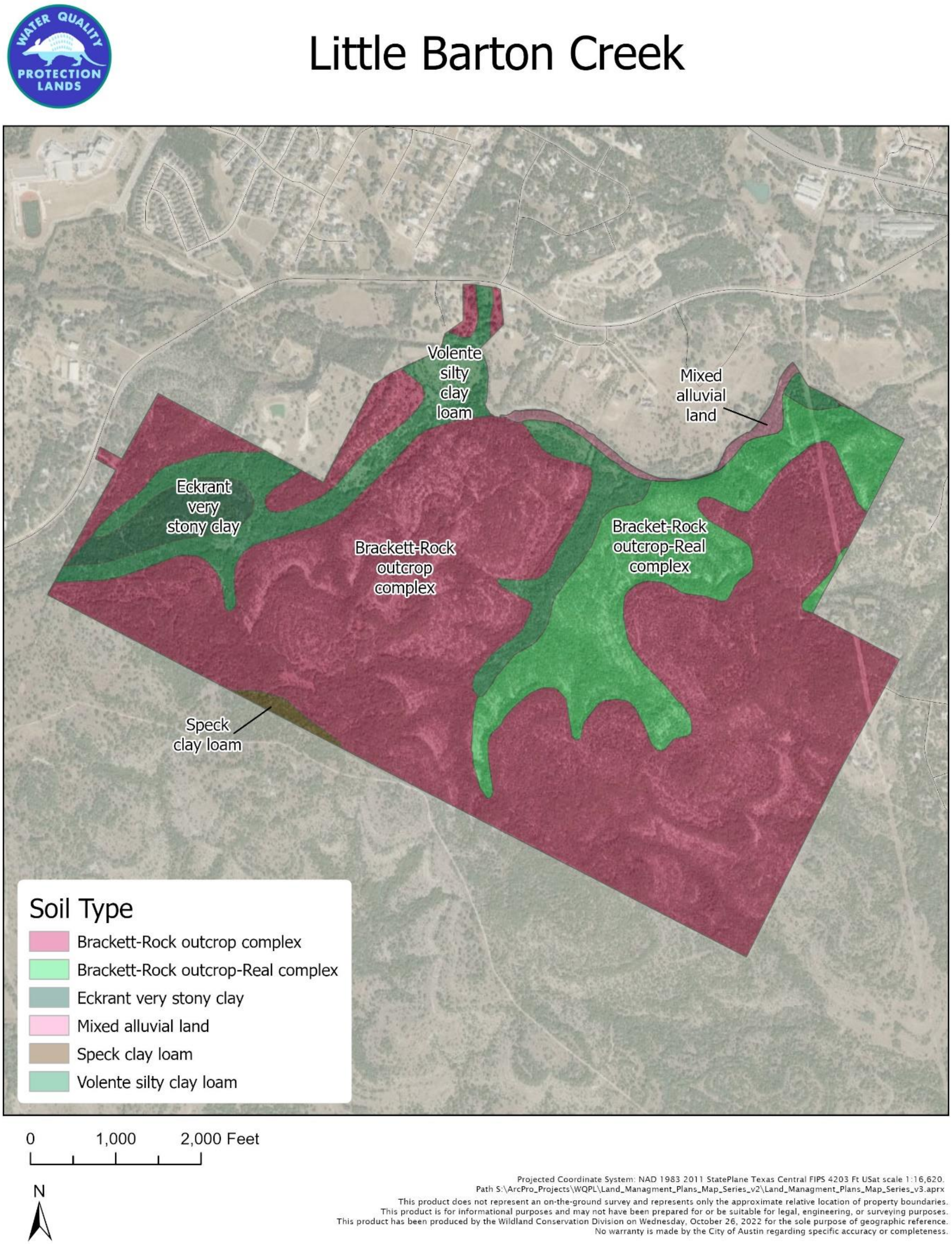

Figure 7: Soil types of Little Barton Creek management unit.

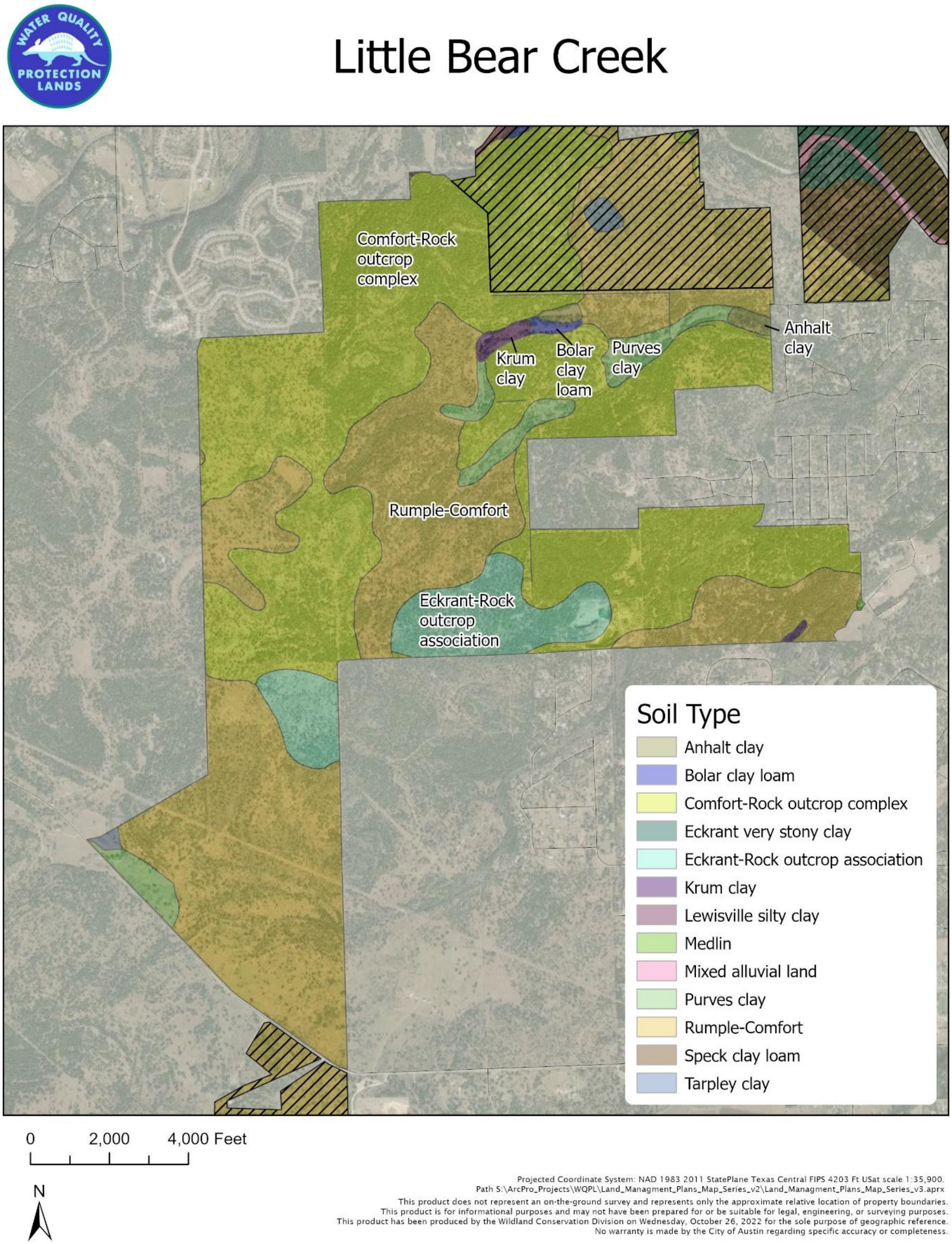

Figure 8: Soil types of Little Bear Creek management unit.

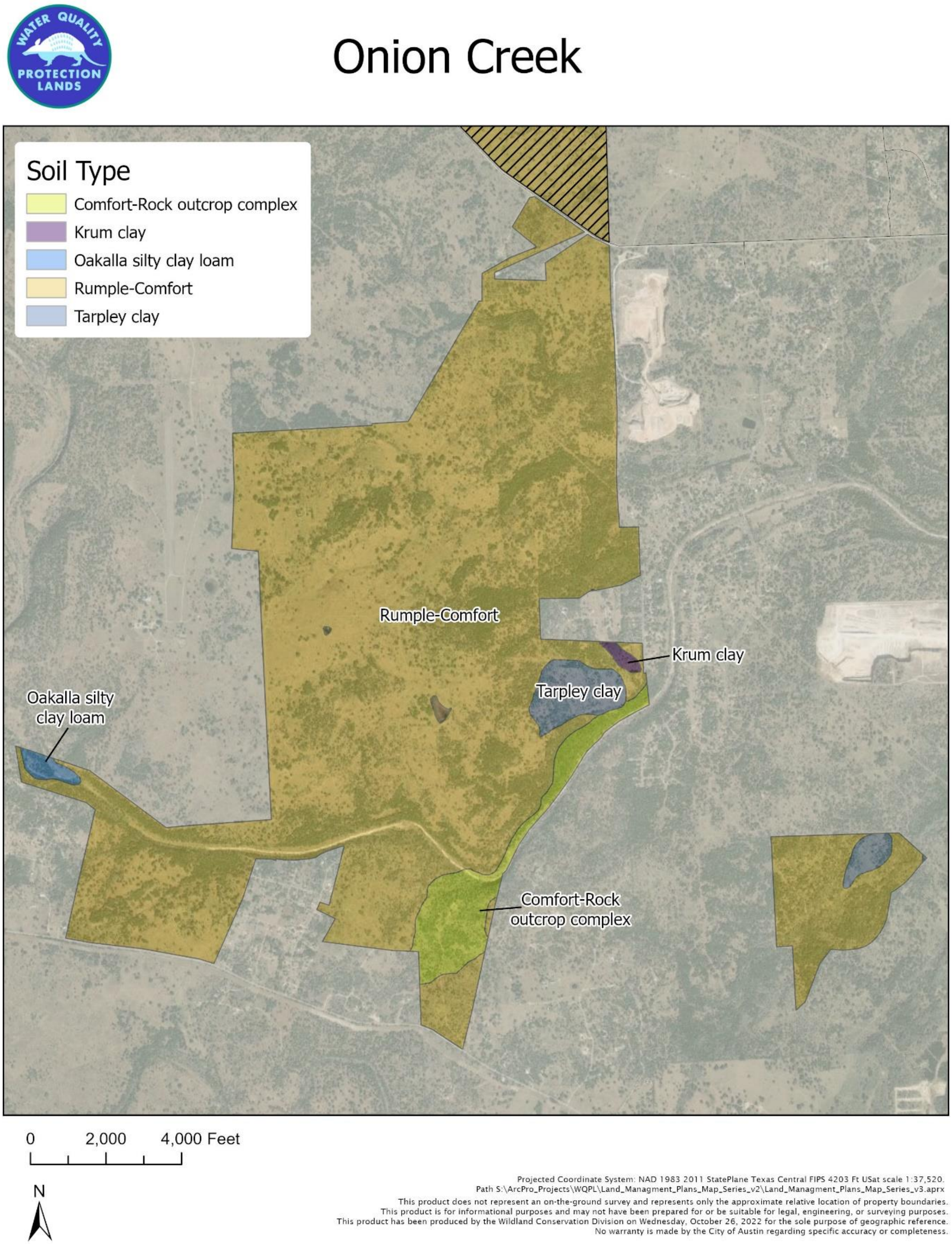

Figure 9: Soil types of Onion Creek management unit.

Figure 10: Soil types of Slaughter Creek management unit.

Slaughter Creek (Brodie Wild)

Figure 11: Soil types of Slaughter Creek (Brodie Wild) management unit.

Slaughter Creek (MGM)

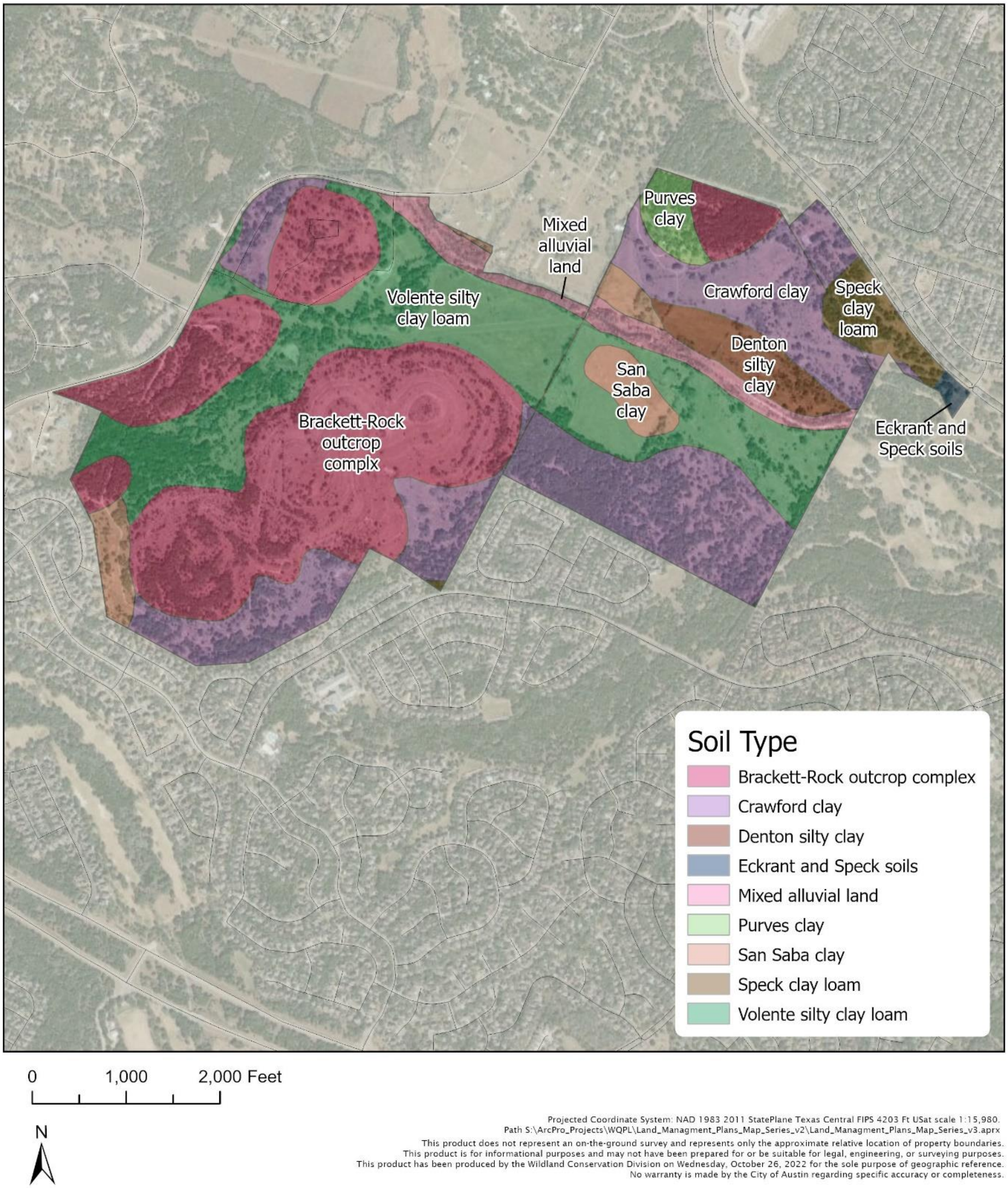

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Figure 12: Soil types of Slaughter Creek (Mary Gay Maxwell) management unit.

Barton Creek

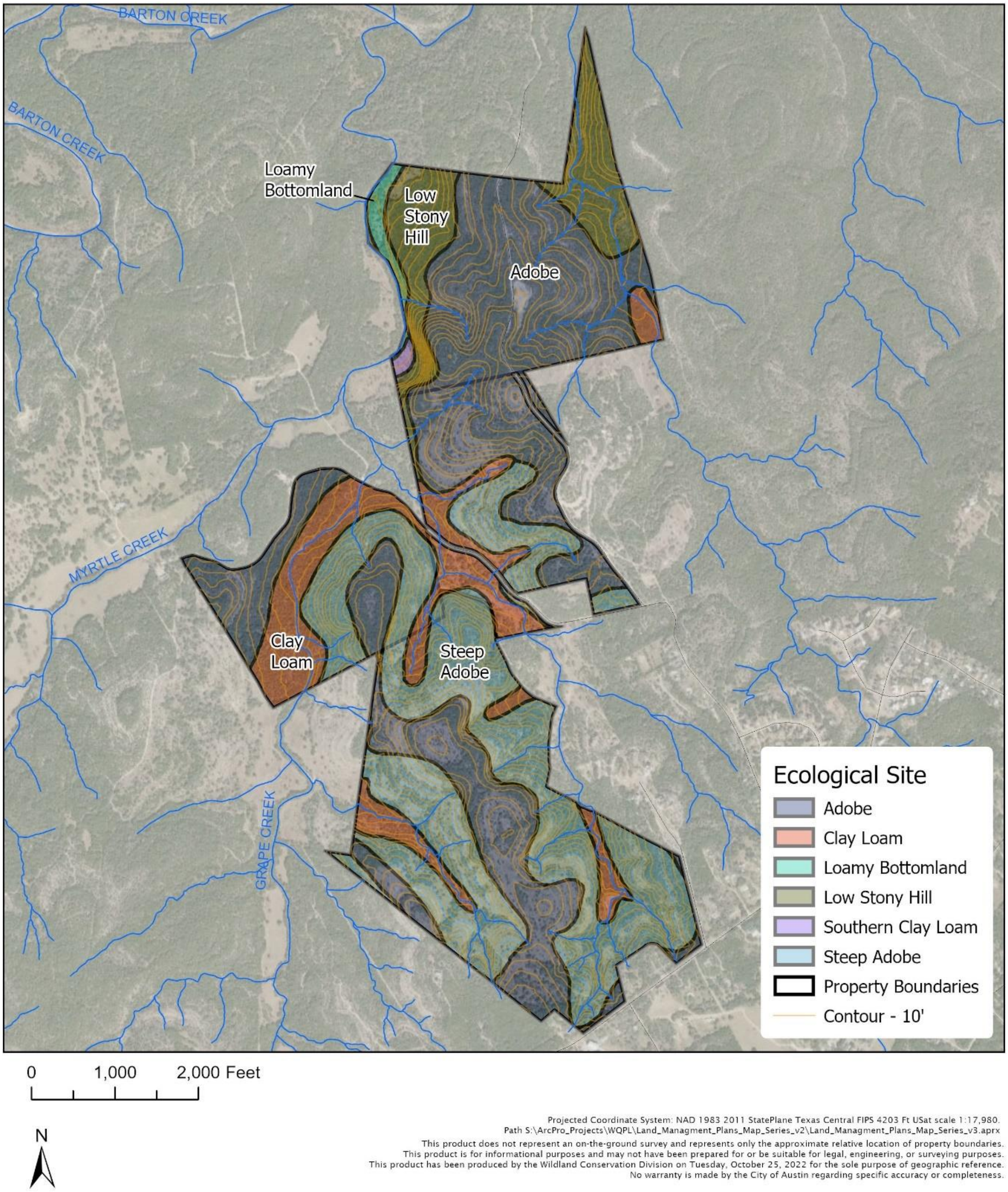

Figure 13: Ecological sites of Barton Creek management unit.

Barton Creek (Shudde Fath)

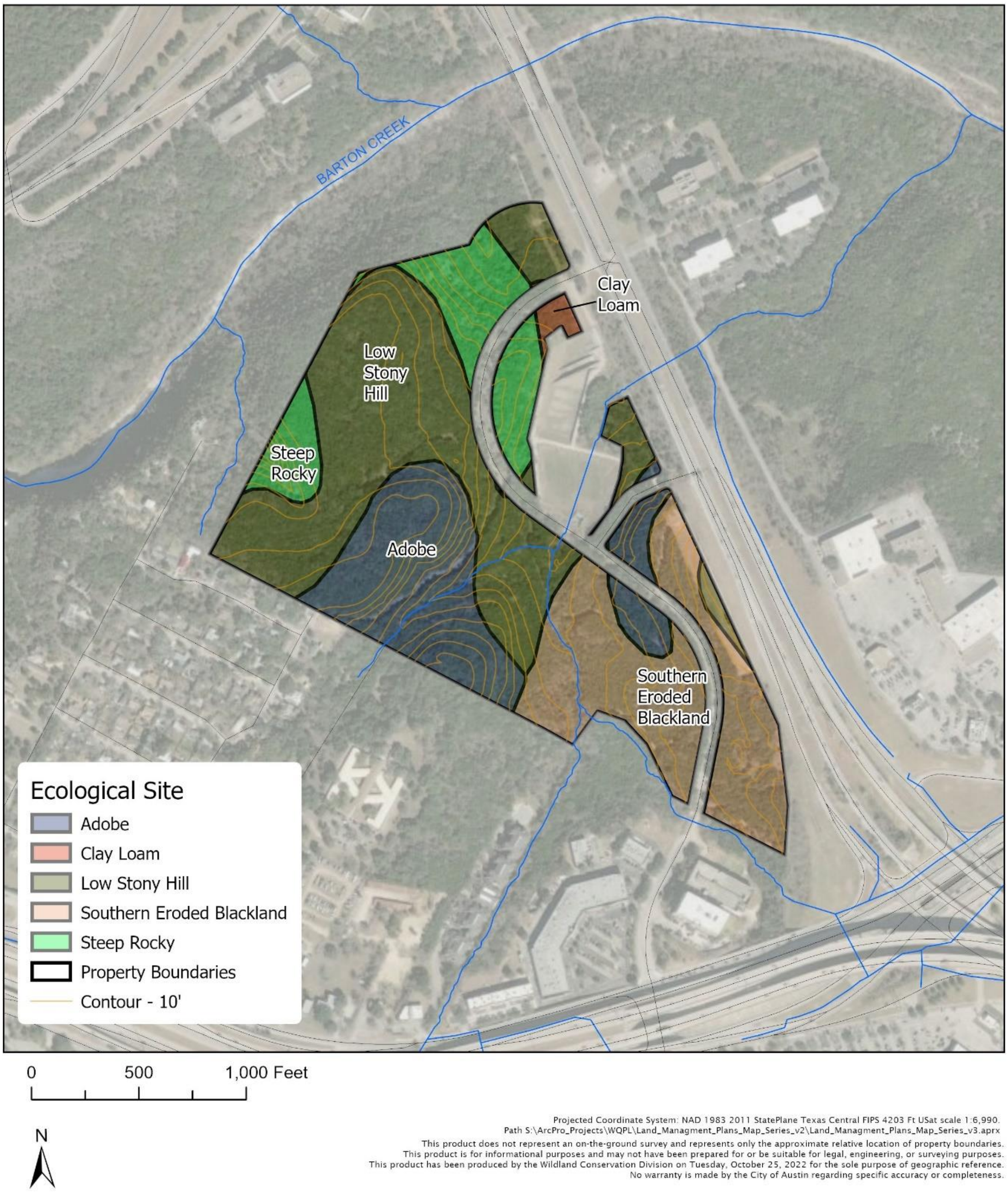

Figure 14: Ecological sites of Barton Creek (Shudde Fath) management unit.

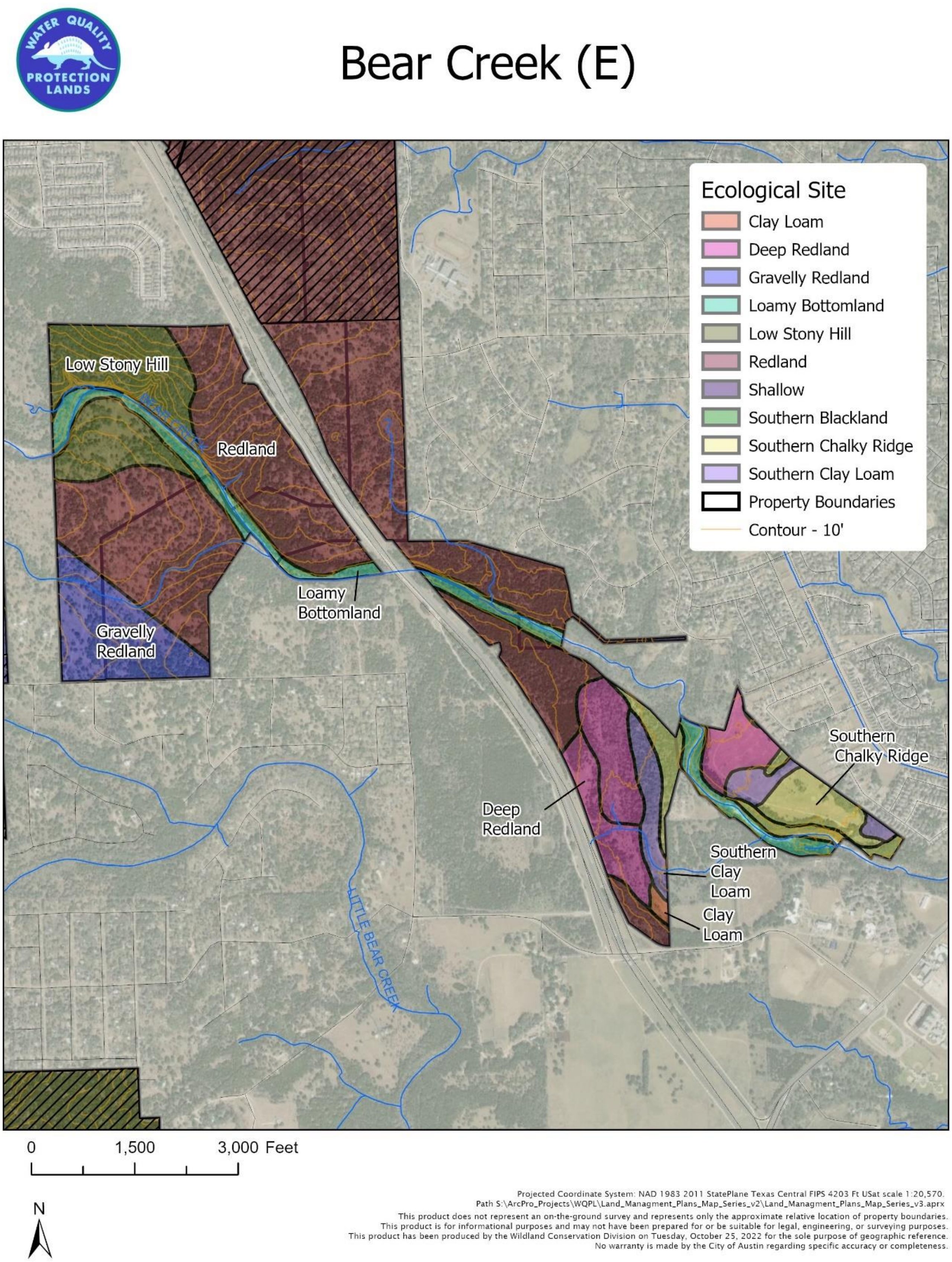

Figure 15: Ecological sites of Bear Creek management unit (eastern side).

Bear Creek (W)

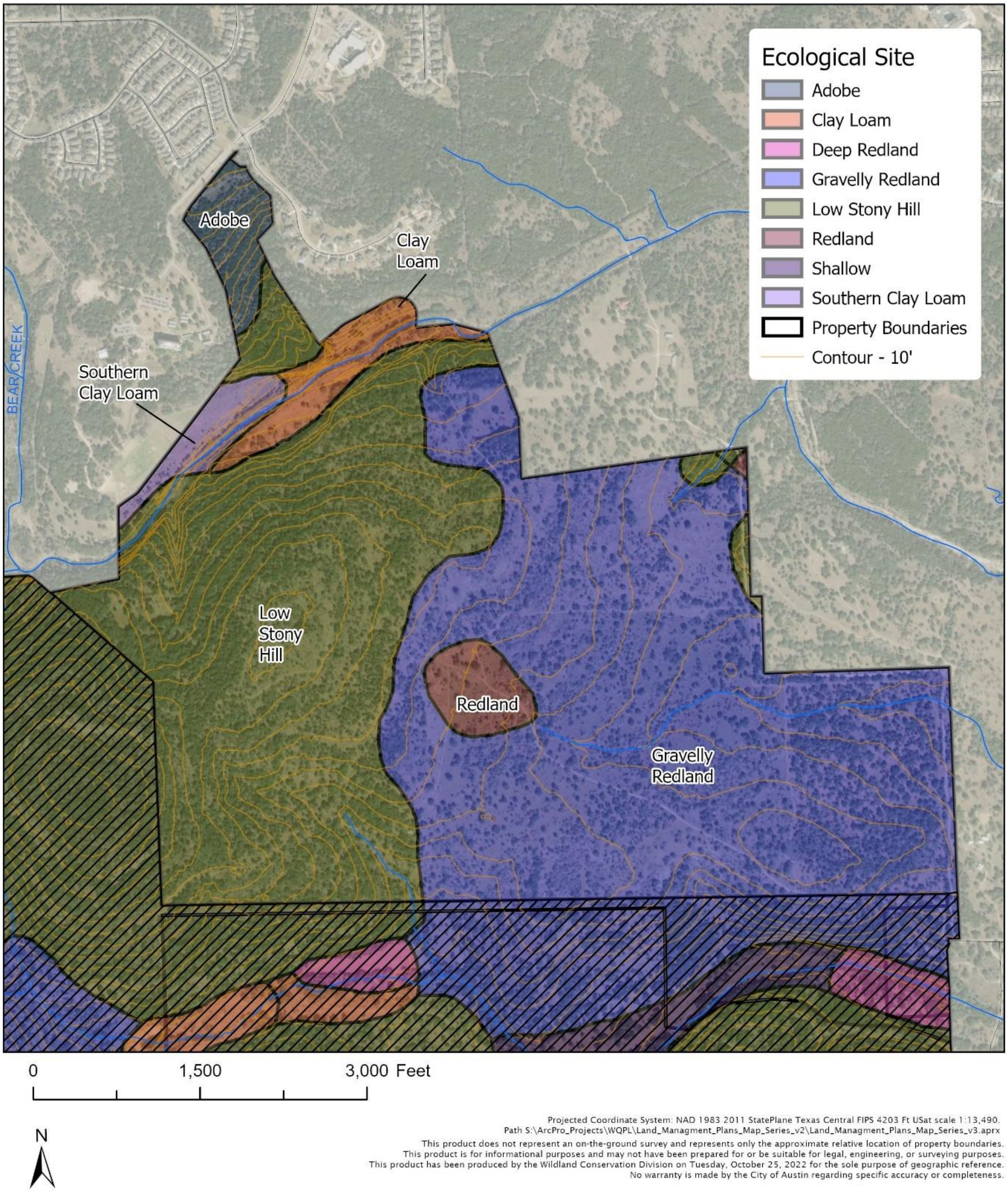

Figure 16: Ecological sites of Bear Creek management unit (western side).

Bull Creek

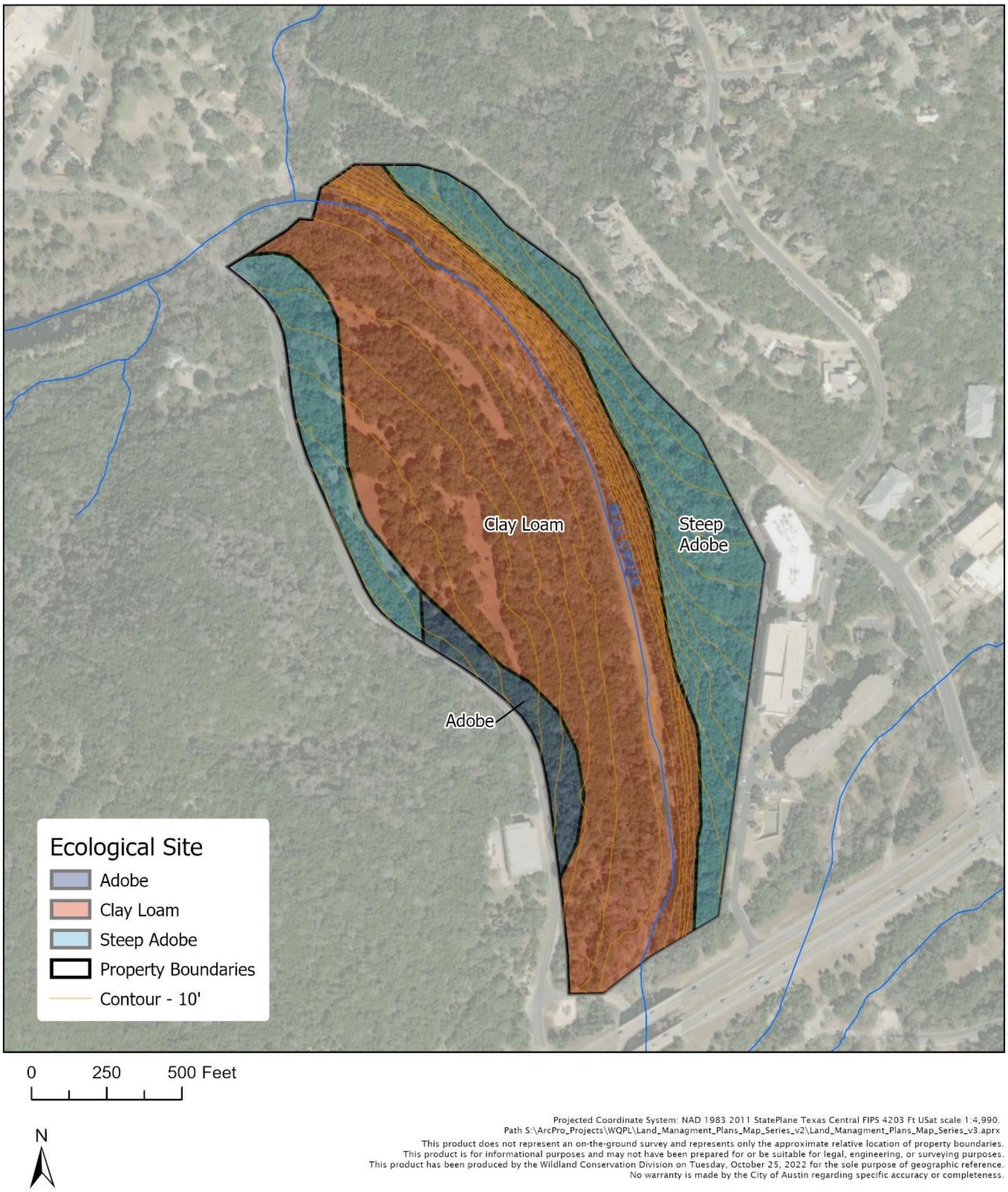

Figure 17: Ecological sites of Bull Creek management unit.

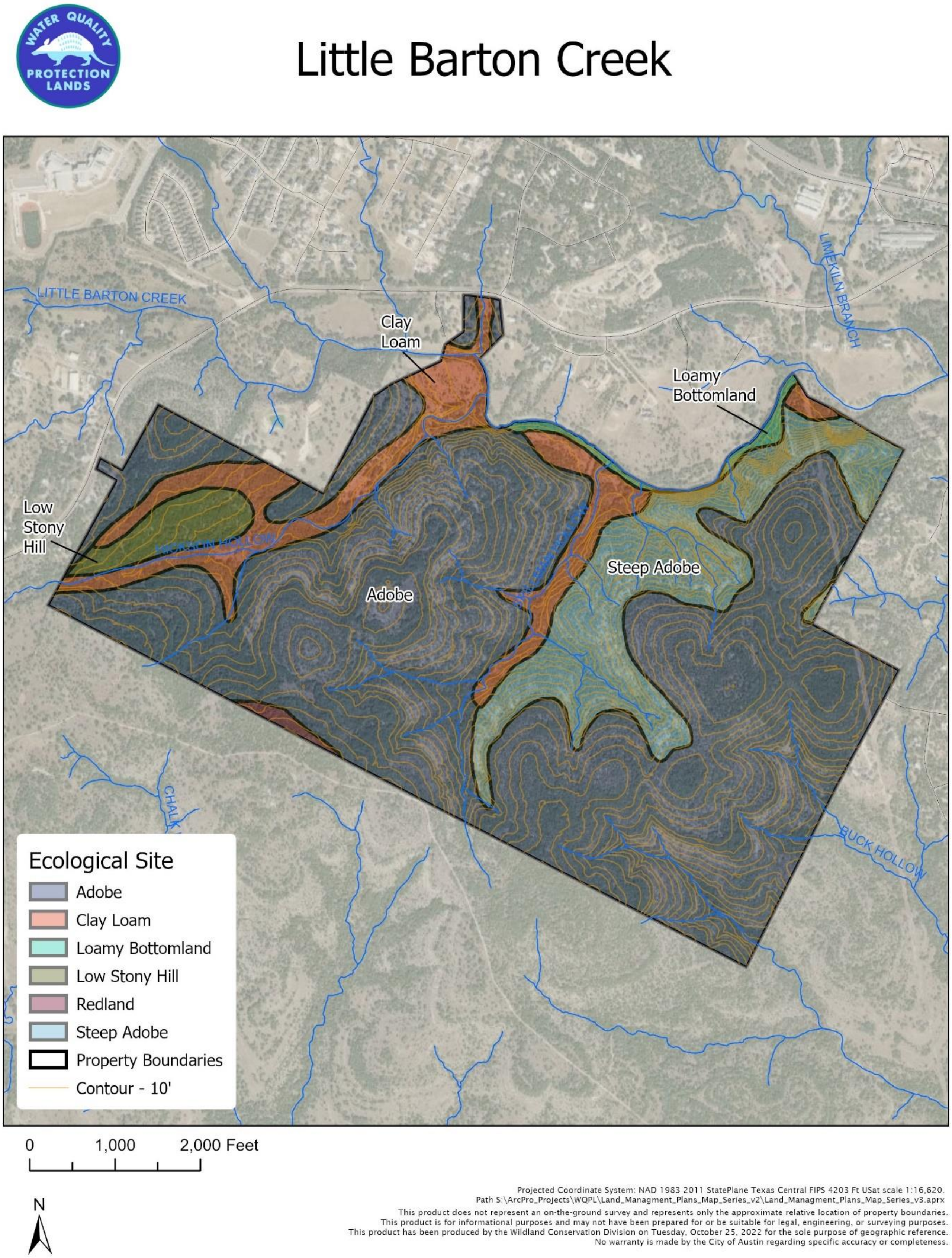

Figure 18: Ecological sites of Little Barton Creek management unit.

Little Bear Creek

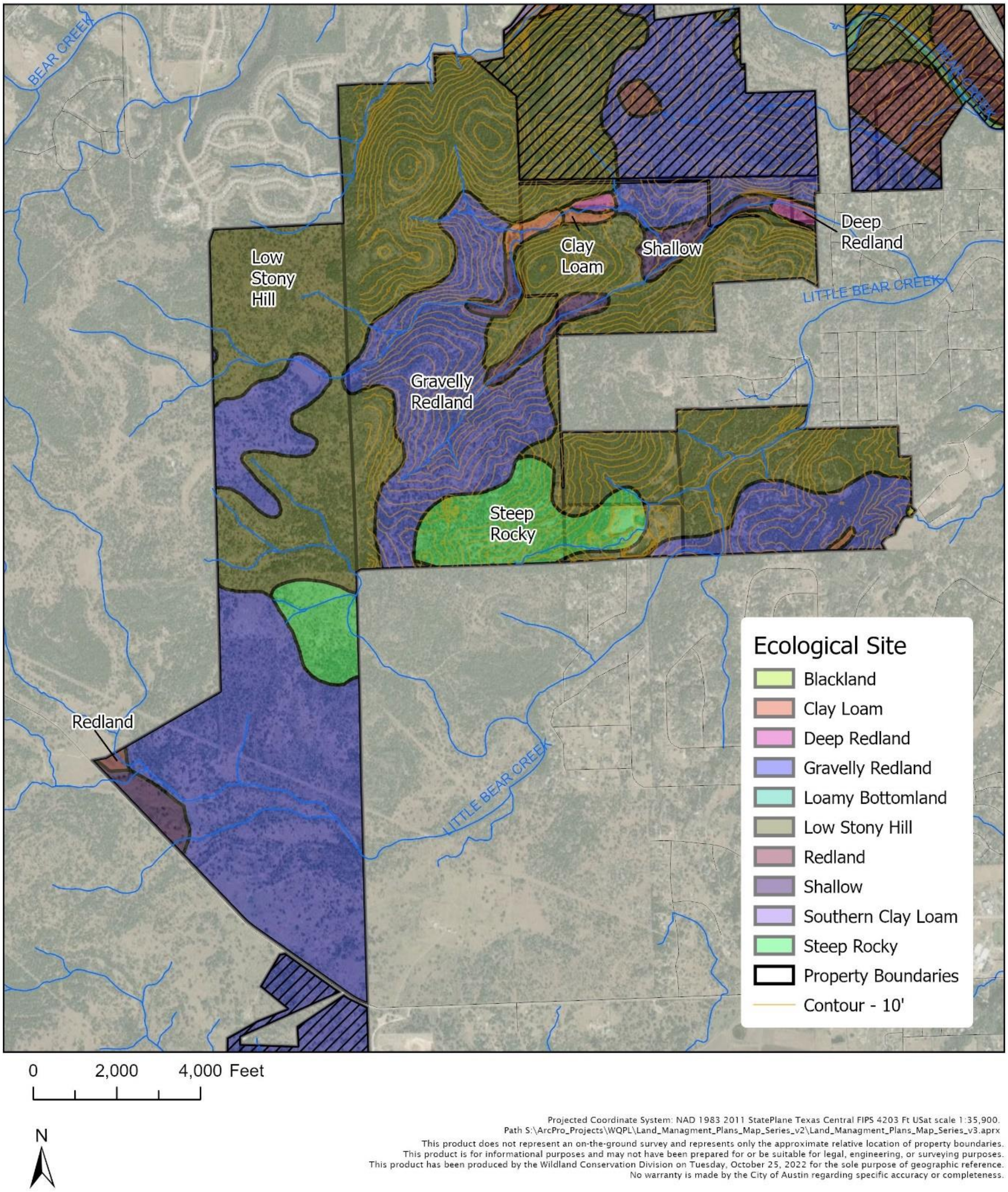

Figure 19: Ecological sites of Little Bear Creek management unit.

Onion Creek

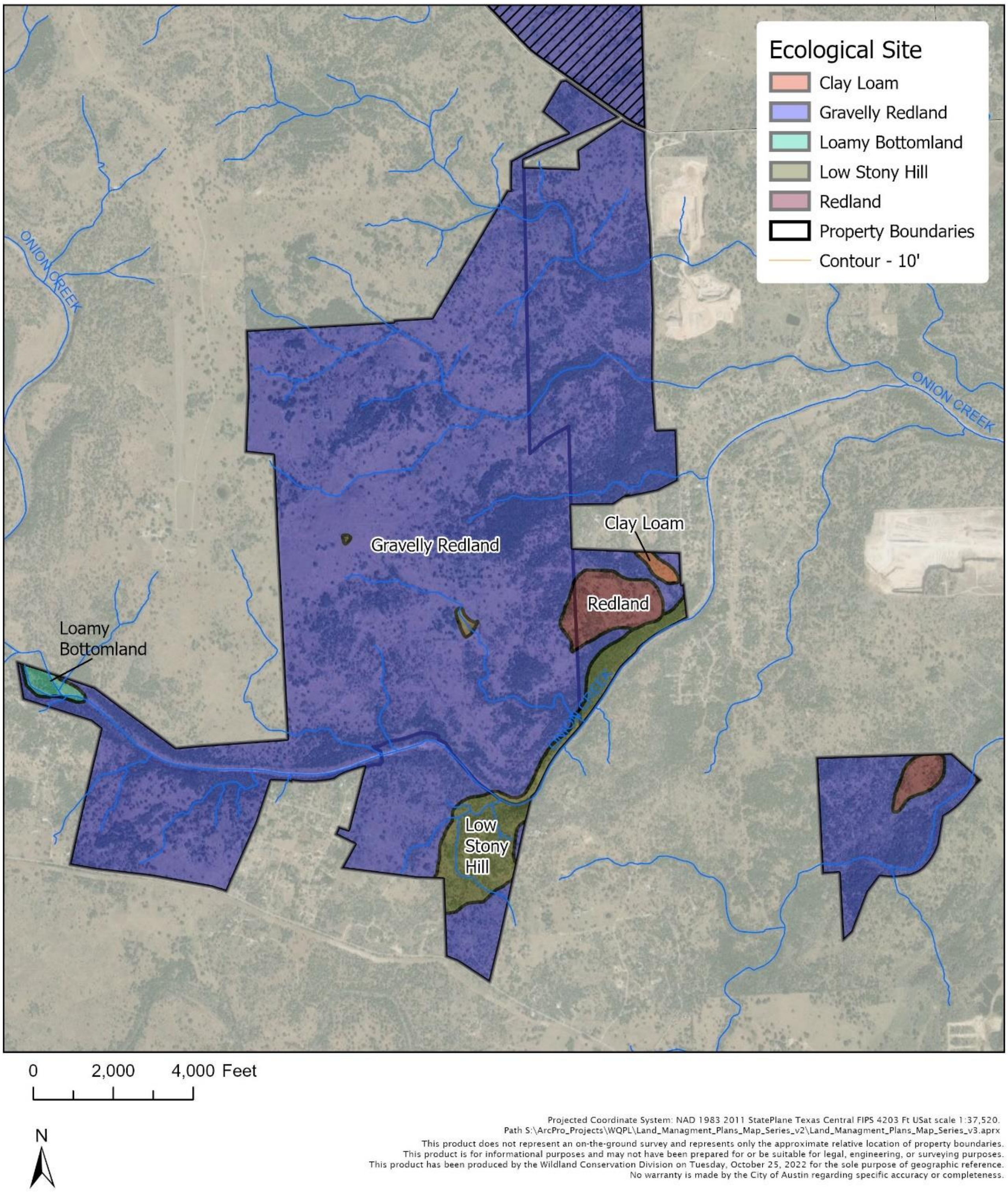

Figure 20: Ecological sites of Onion Creek management unit.

Slaughter Creek

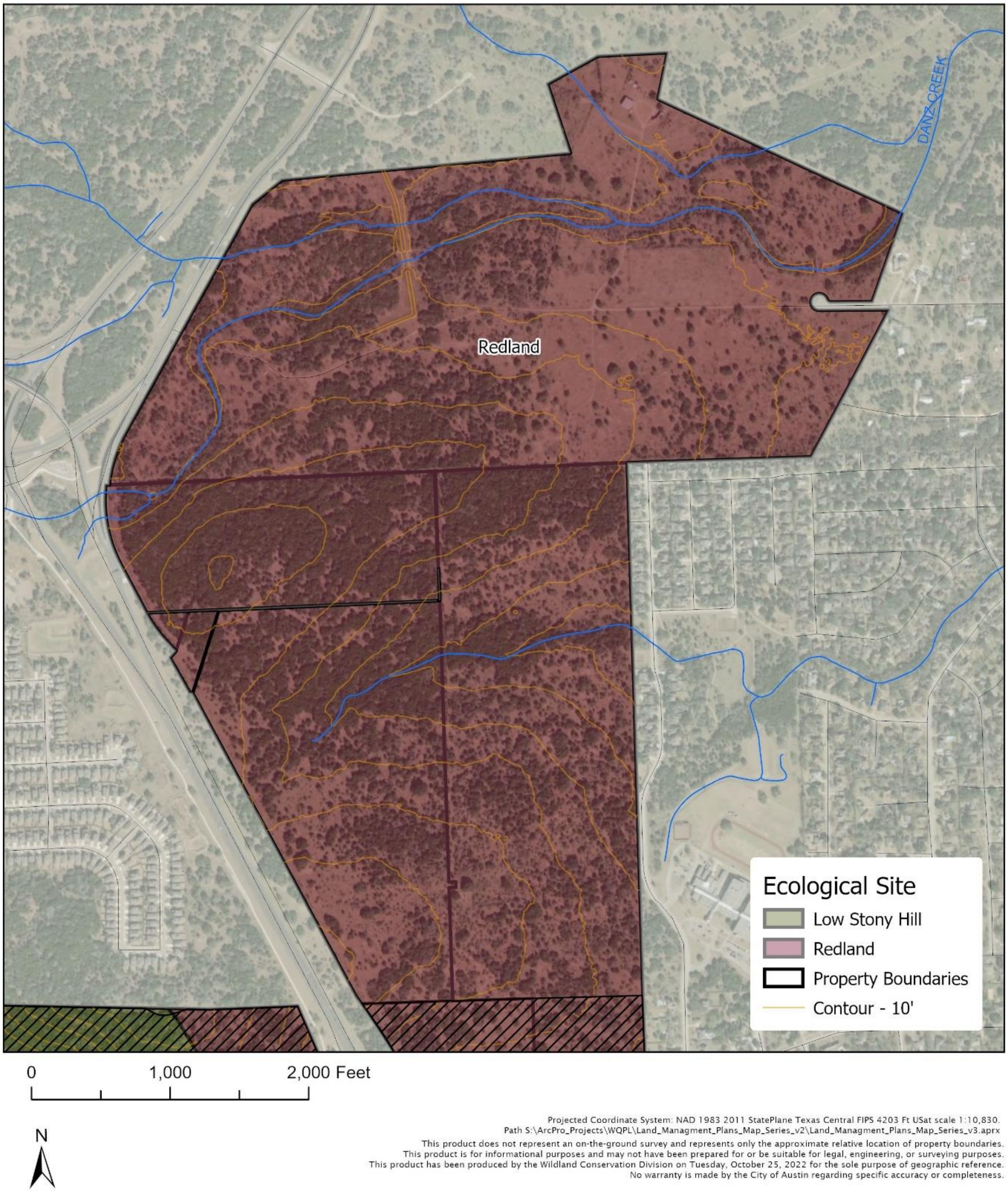

Figure 21: Ecological sites of Slaughter Creek management unit.

Slaughter Creek (Brodie Wild)

Projected Coordinate System: NAD 1983 2011 StatePlane Texas Central FIPS 4203 Ft USat scale 1:2,000.
Path S:\ArcPro_Projects\WQPL\Land_Managment_Plans_Map_Series_v2\Land_Managment_Plans_Map_Series_v3.aprx
This product does not represent an on-the-ground survey and represents only the approximate relative location of property boundaries.
This product is for informational purposes and may not have been prepared for or be suitable for legal, engineering, or surveying purposes.
This product has been produced by the Wildland Conservation Division on Tuesday, October 25, 2022 for the sole purpose of geographic reference.
No warranty is made by the City of Austin regarding specific accuracy or completeness.

Figure 22: Ecological sites of Slaughter Creek (Brodie Wild) management unit.

Slaughter Creek (MGM)

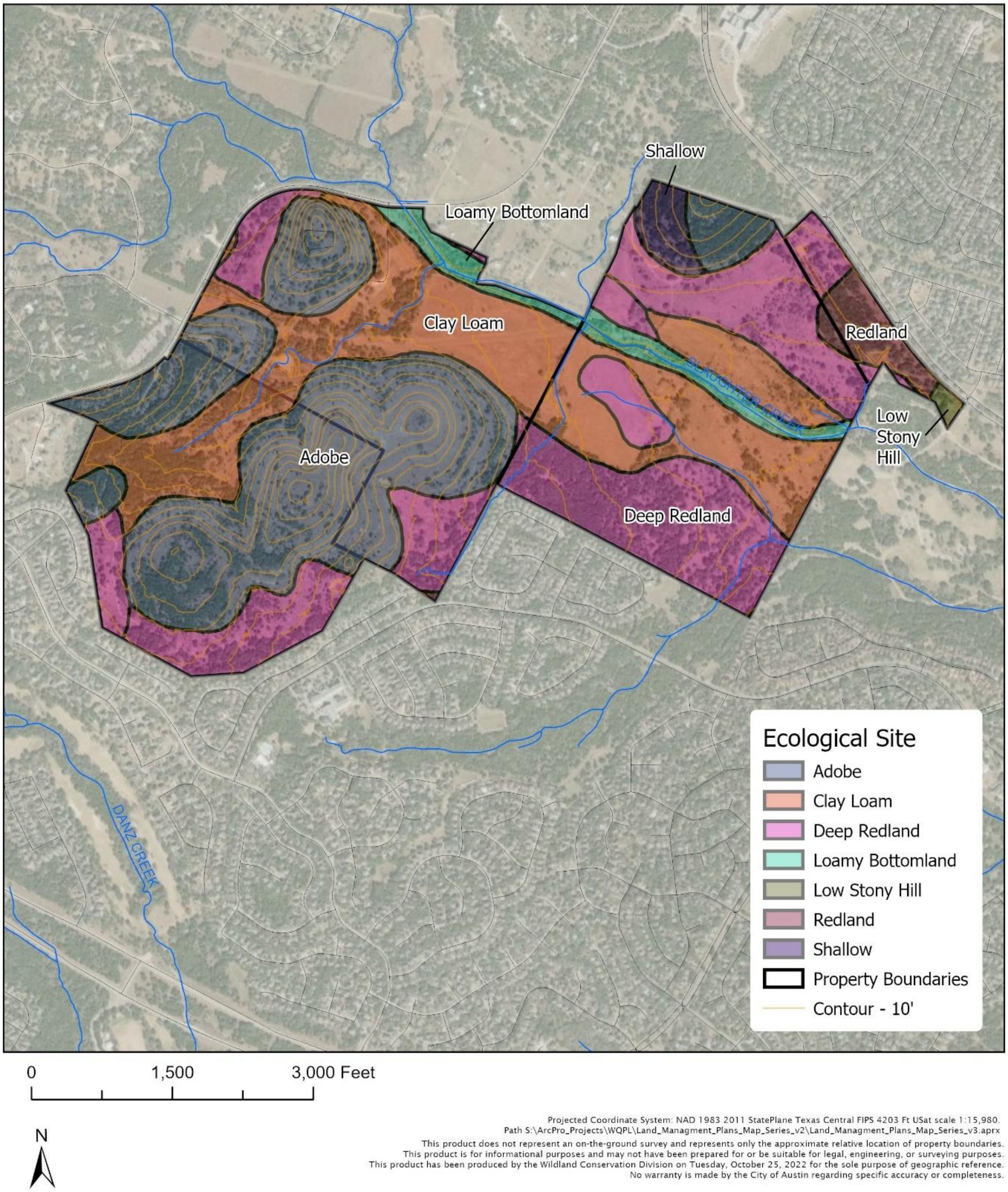

Figure 23: Ecological sites of Slaughter Creek (Mary Gay Maxwell) management unit.

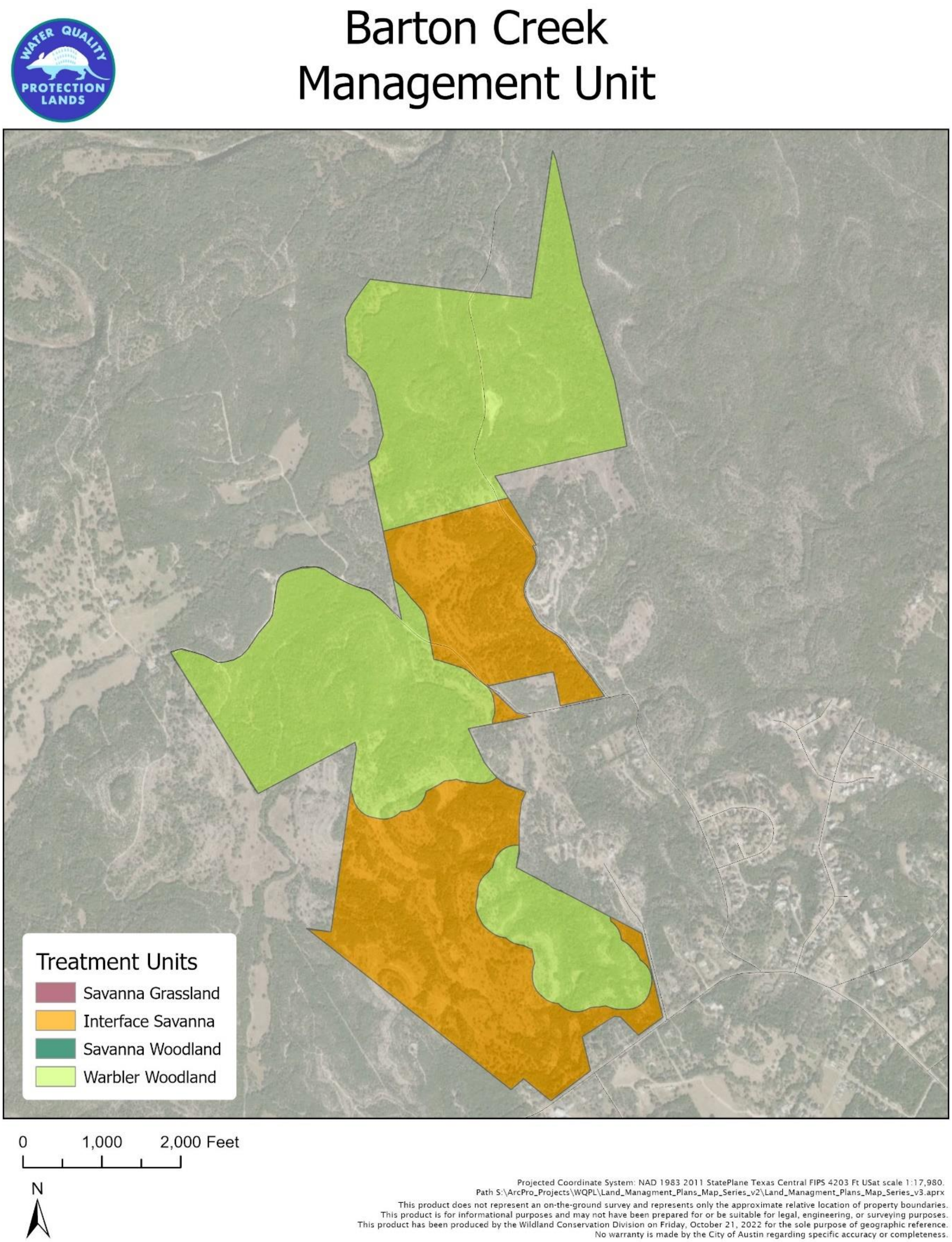

Figure 24: Land cover categories of Barton Creek management unit.

Figure 25: Land cover categories of Barton Creek (Shudde Fath) management unit.

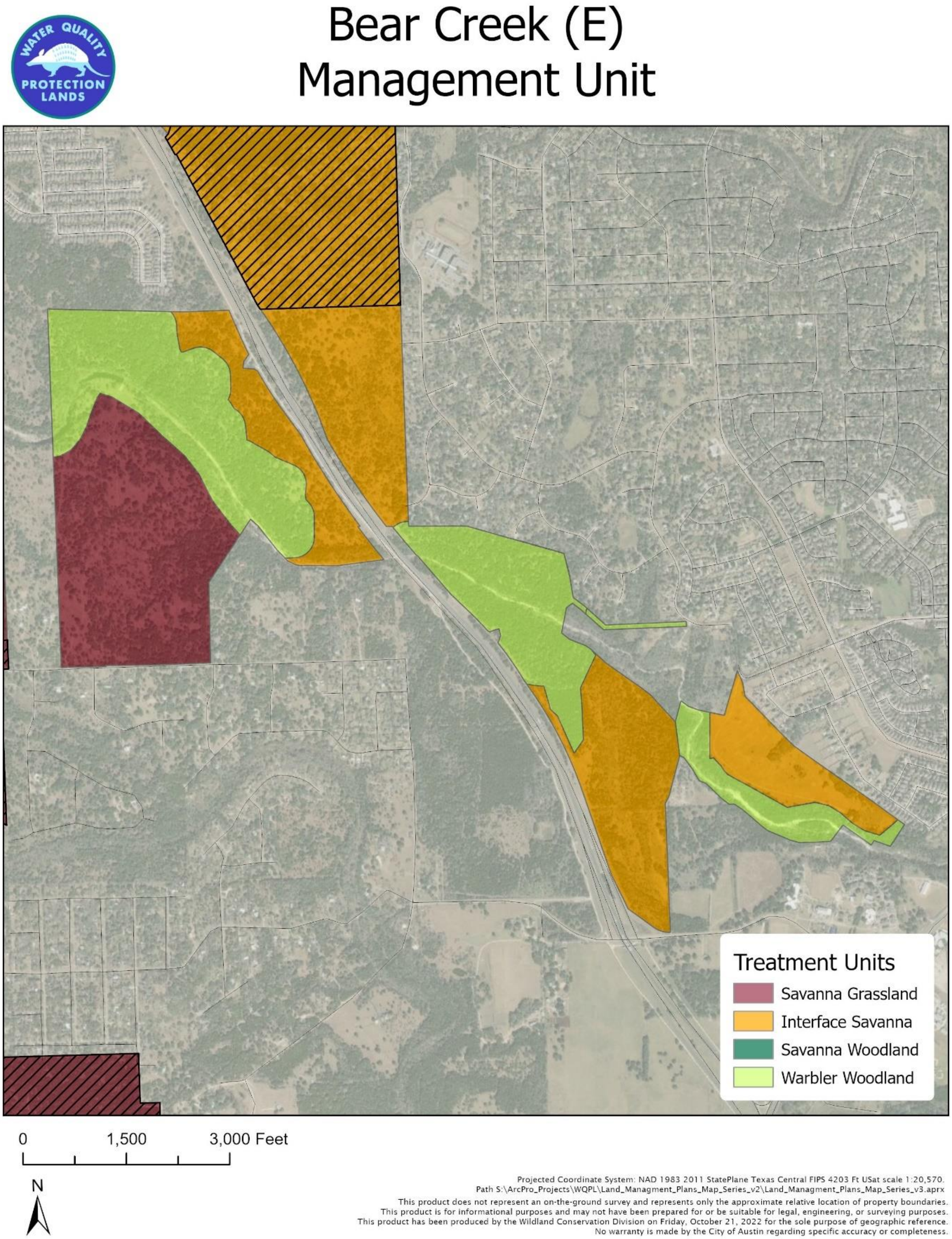

Figure 26: Land cover categories of Bear Creek management unit (easter side).

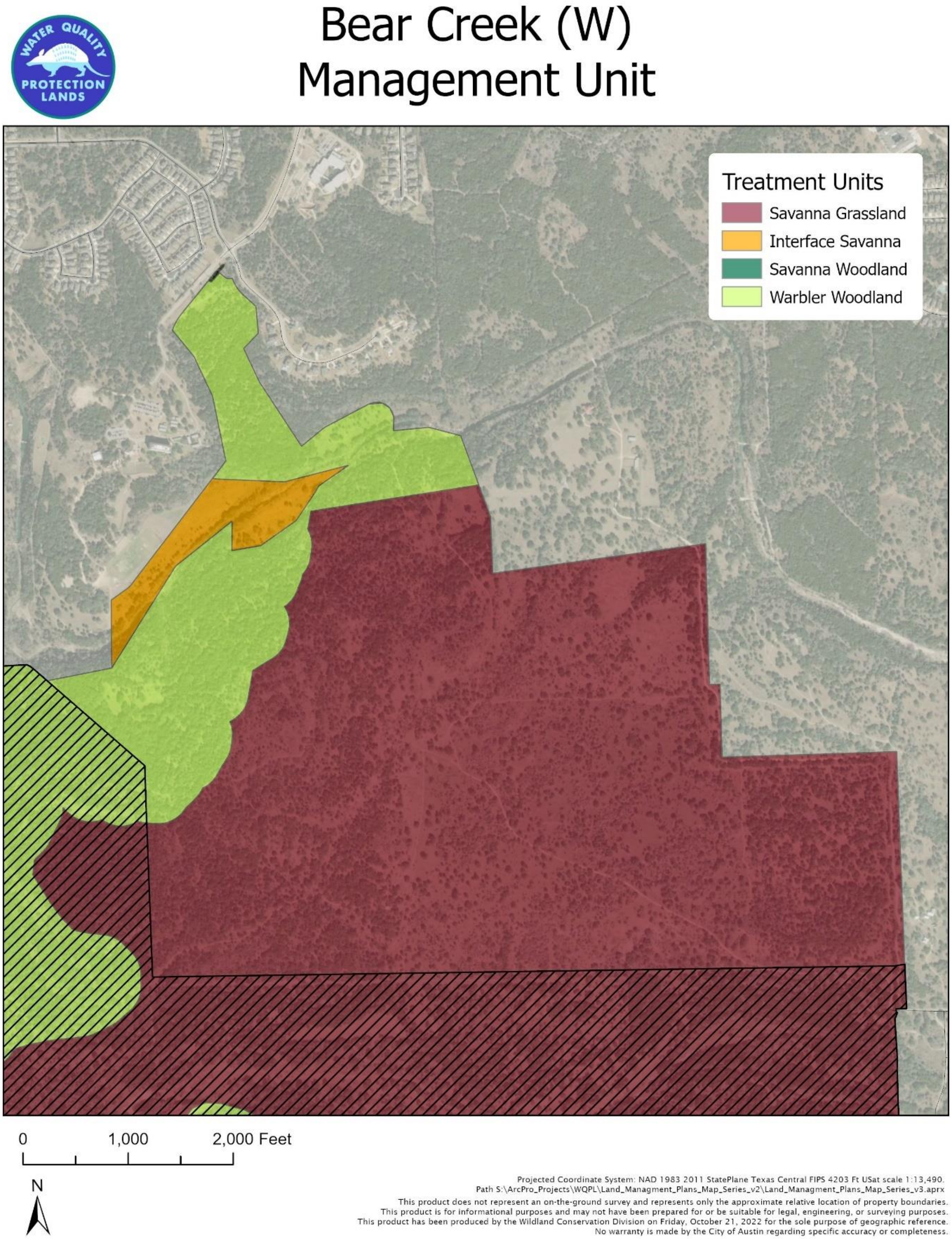

Figure 27: Land cover categories of Bear Creek management unit (western side).

Figure 28: Land cover categories of Bull Creek management unit.

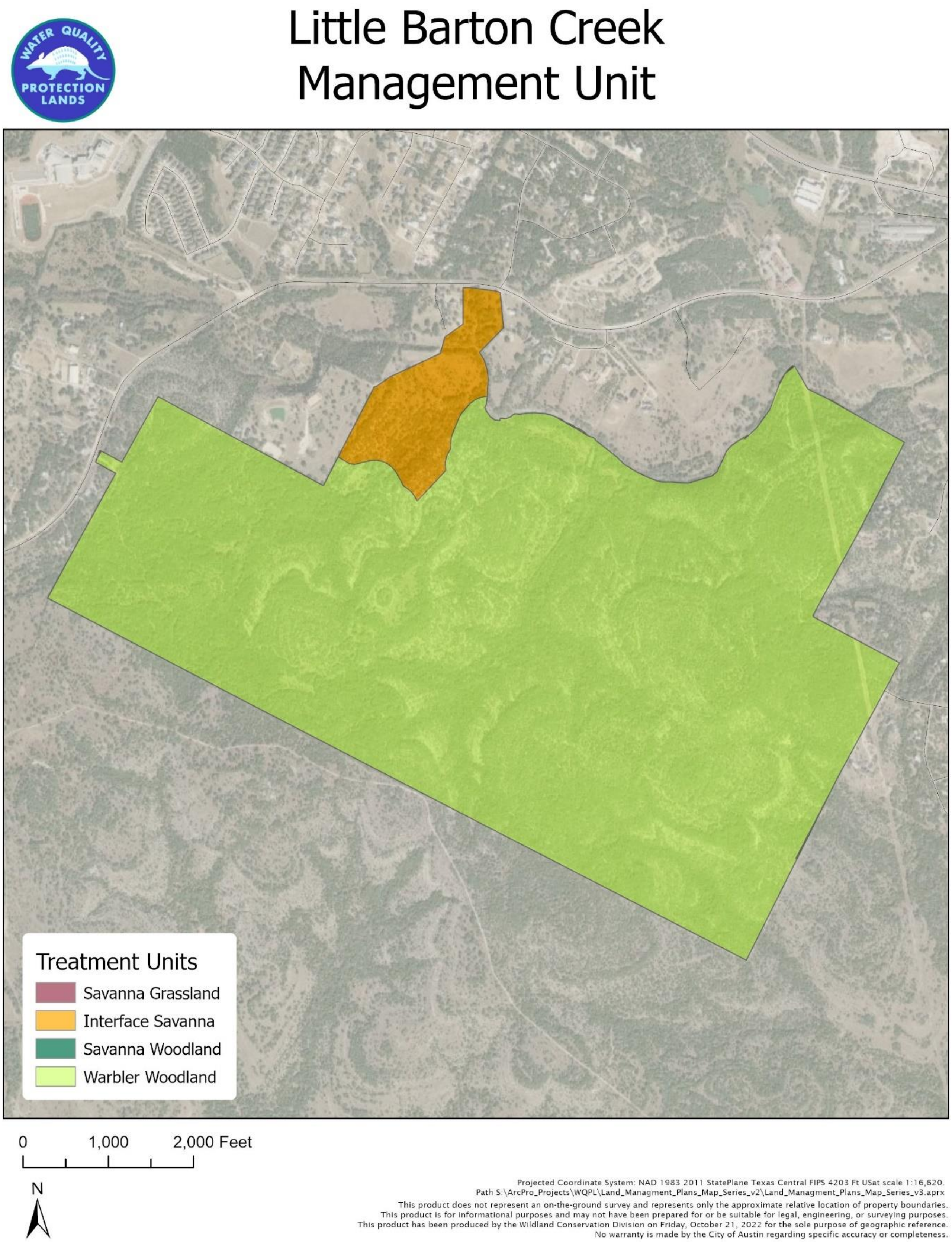

Figure 29: Land cover categories of Little Barton Creek management unit.

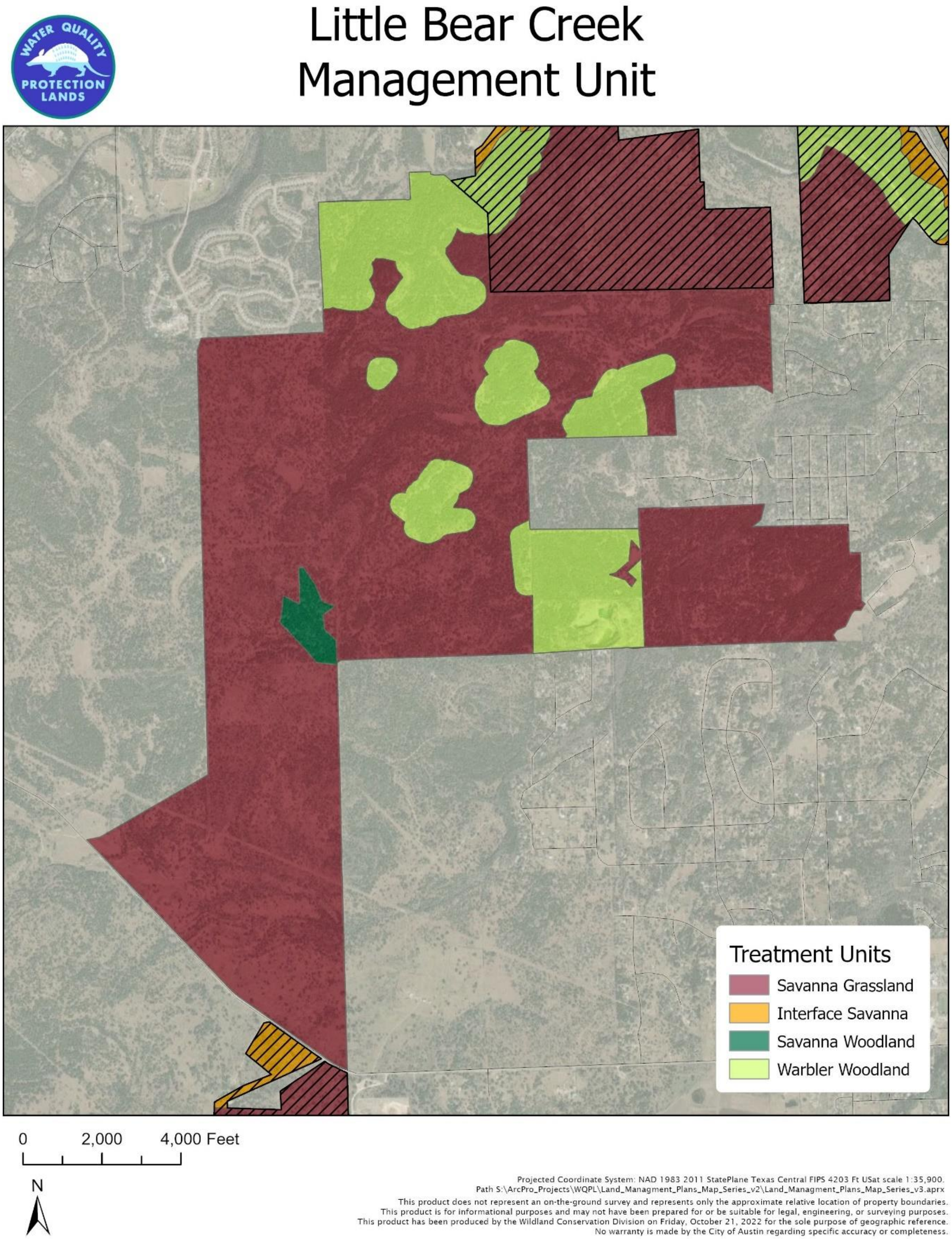

Figure 30: Land cover categories of Little Bear Creek management unit.

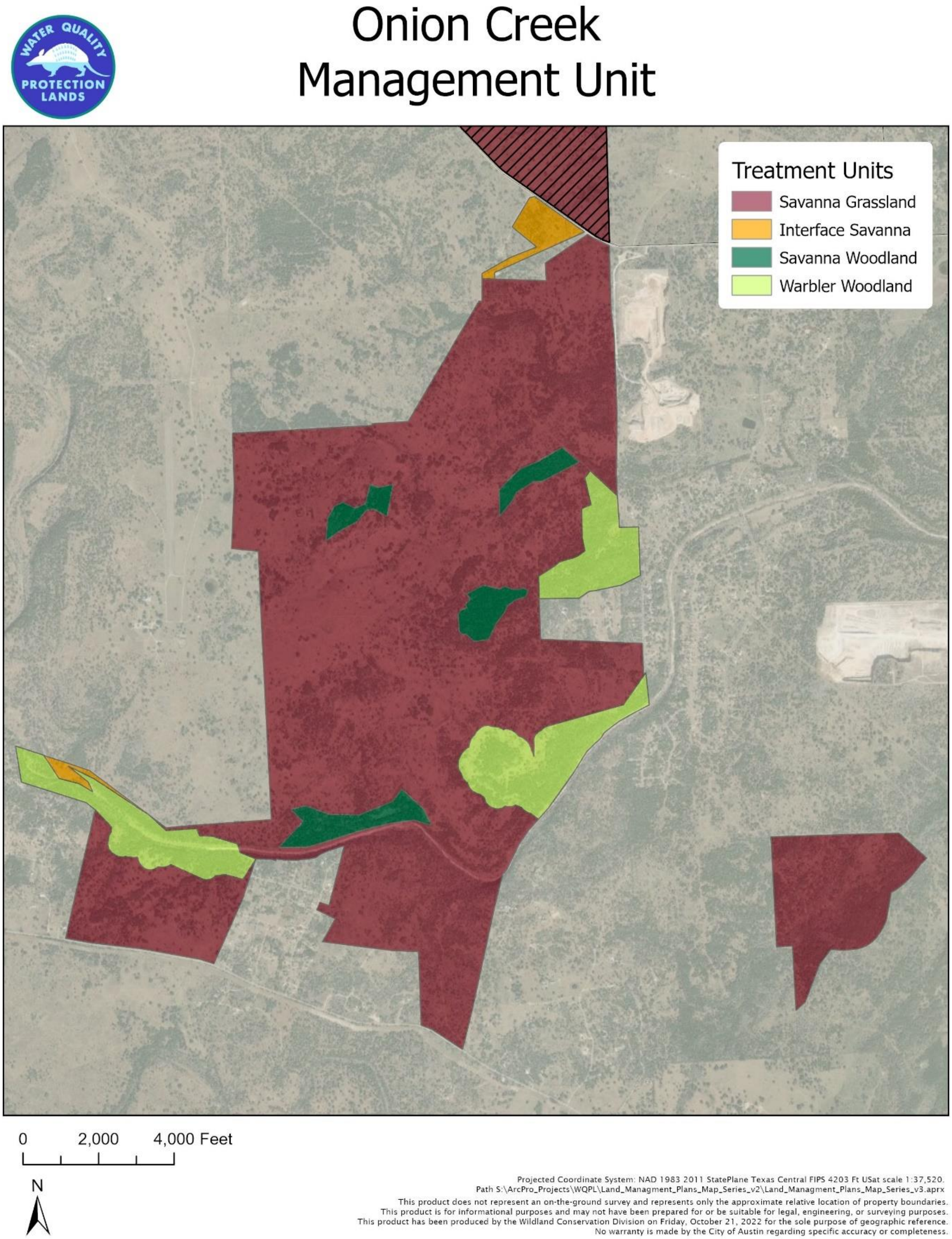

Figure 31: Land cover categories of Onion Creek management unit.

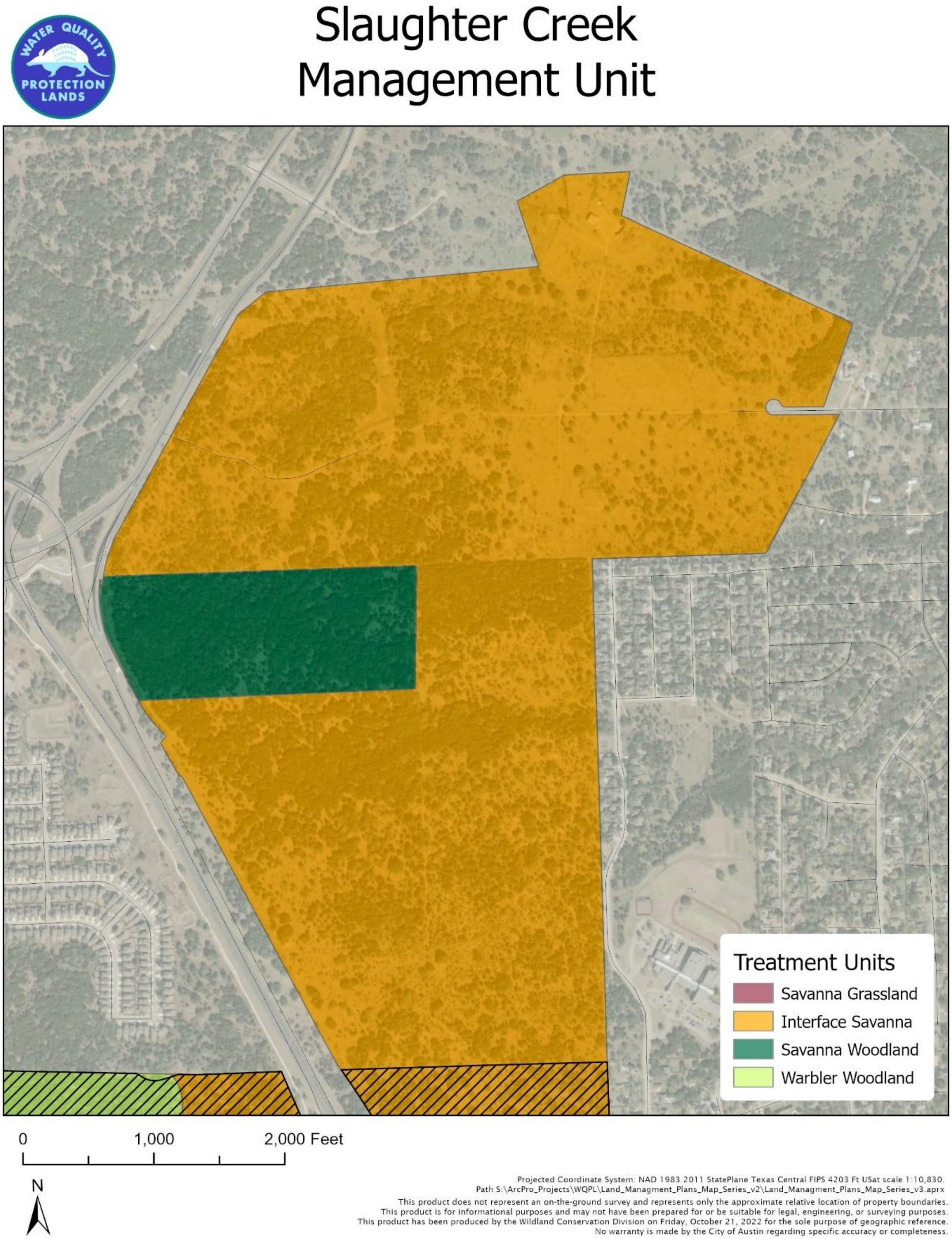

Figure 32: Land cover categories of Slaughter Creek management unit.

Figure 33: Land cover categories of Slaughter Creek (Brodie Wild) management unit.

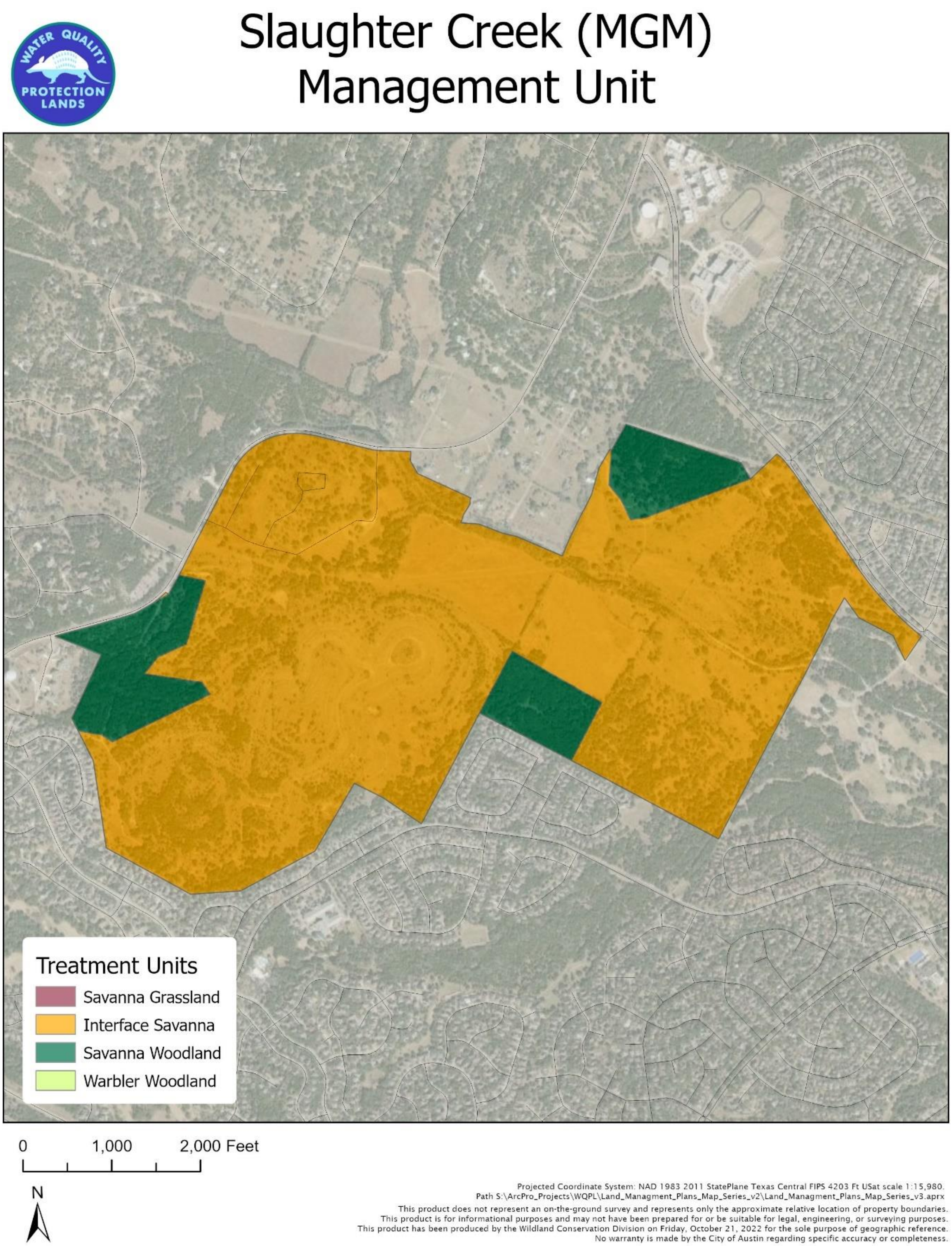

Figure 34: Land cover categories of Slaughter Creek (Mary Gay Maxwell) management unit.

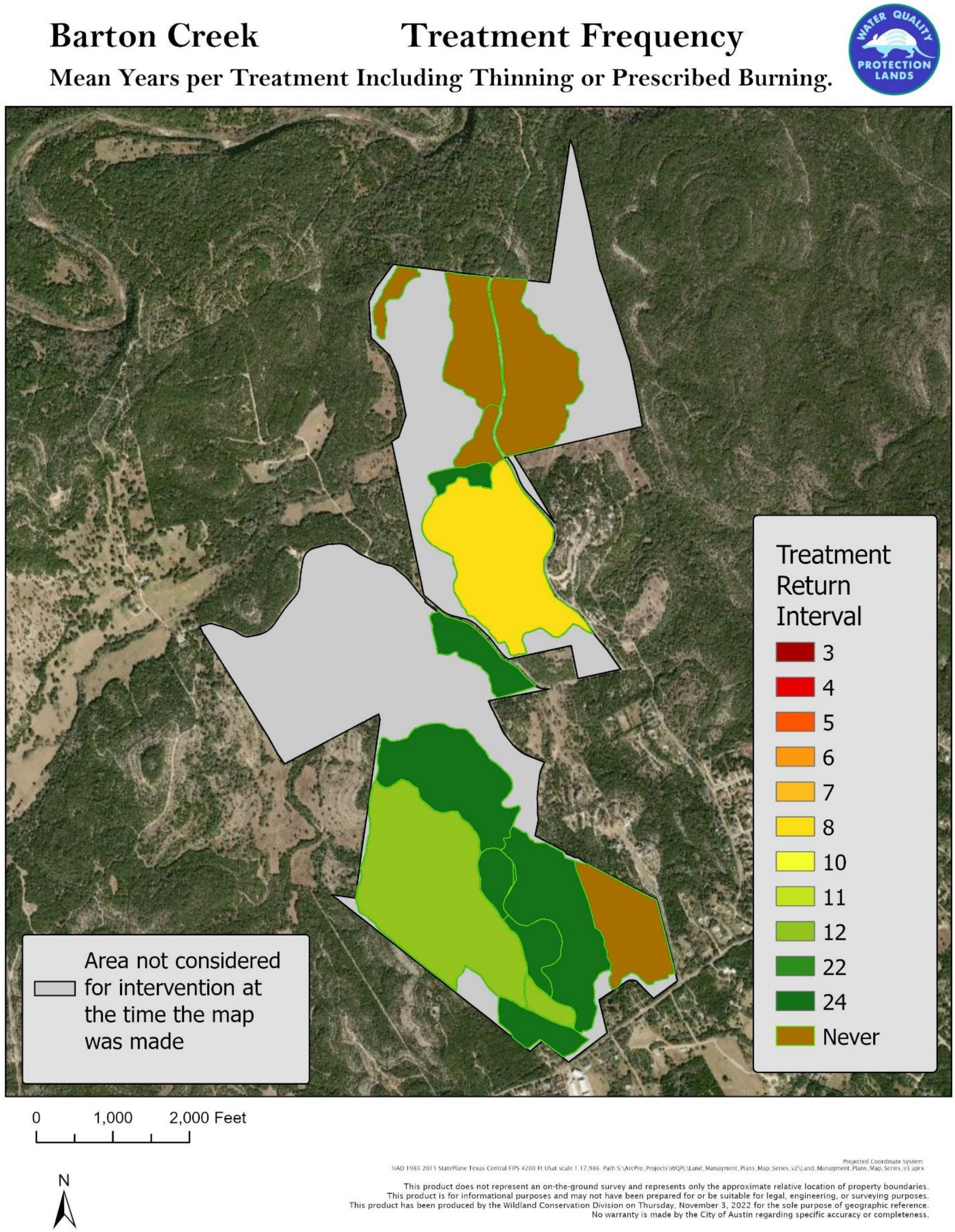

Figure 35: Treatment frequency map for Barton Creek management unit.

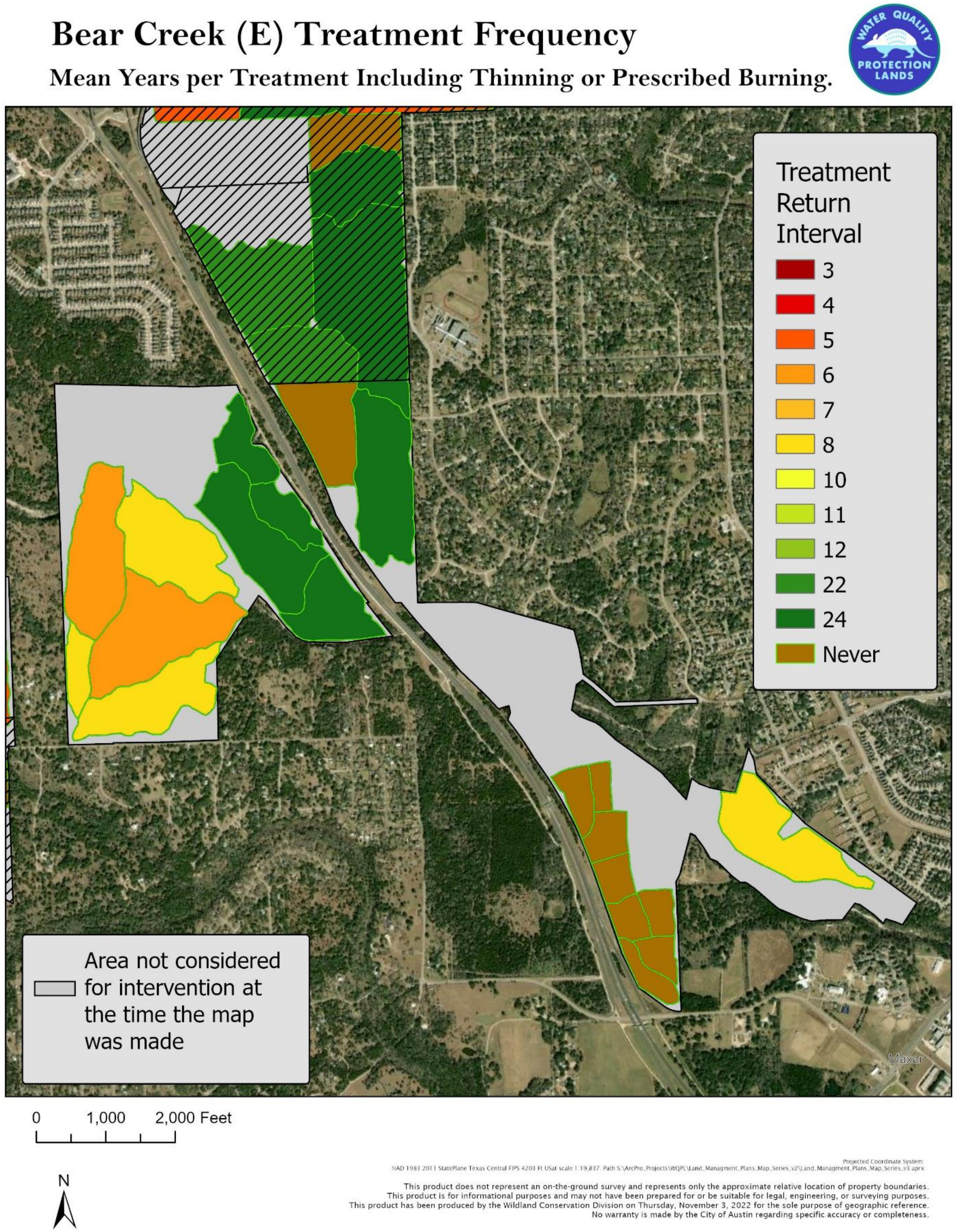

Figure 36: Treatment frequency map for Bear Creek management unit (eastern side).

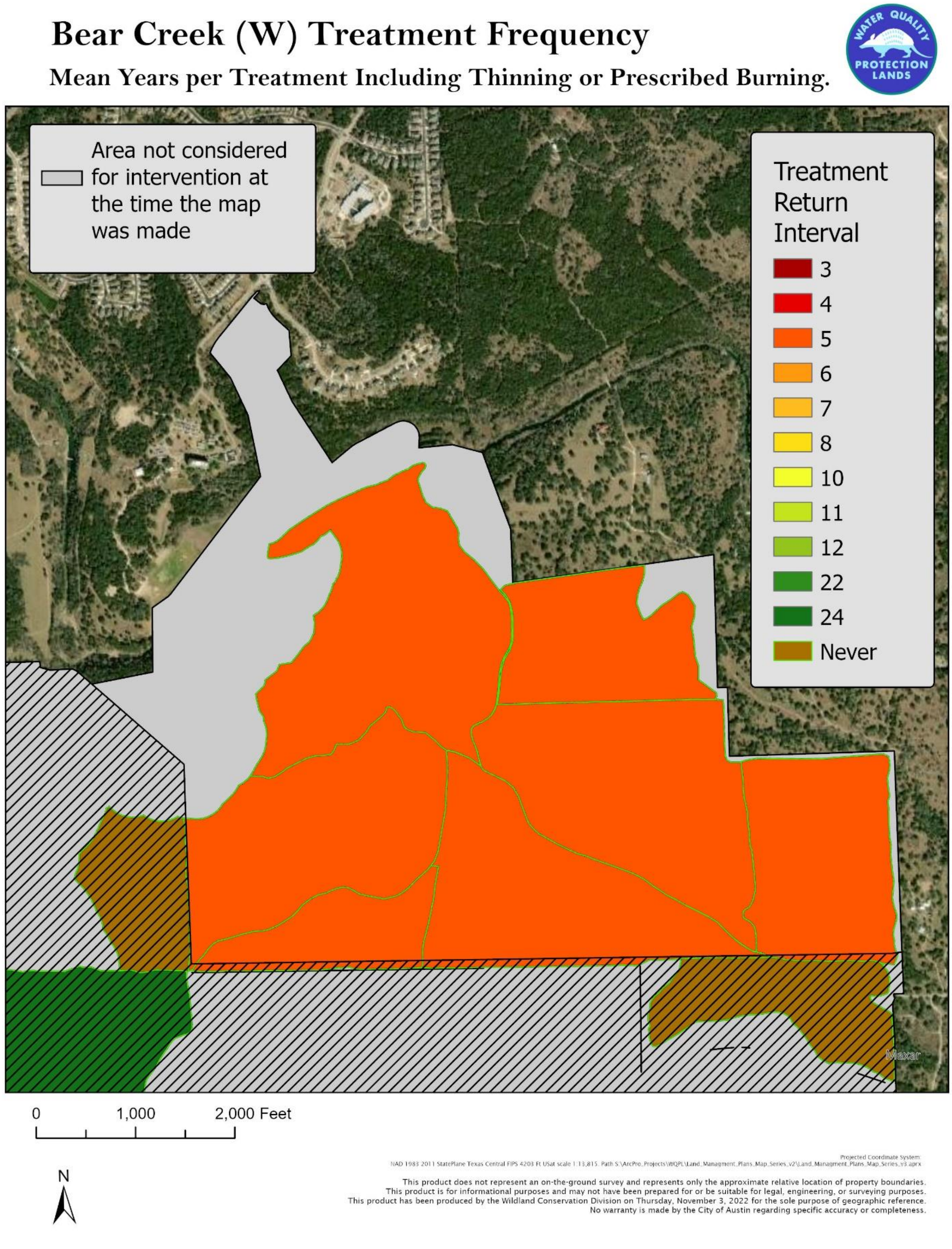

Figure 37: Treatment frequency map for Bear Creek management unit (western side).

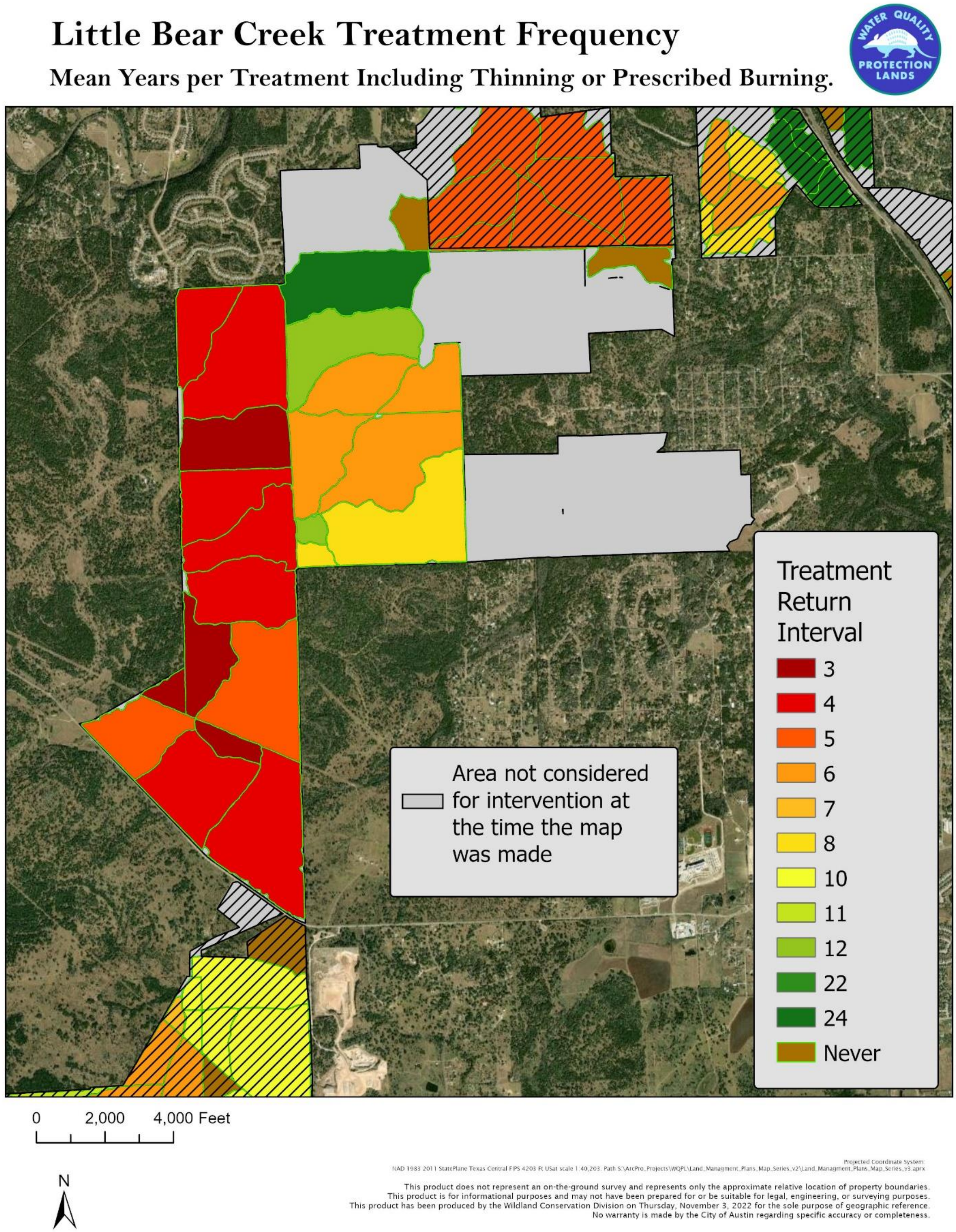

Figure 38: Treatment frequency map for Little Bear Creek management unit.

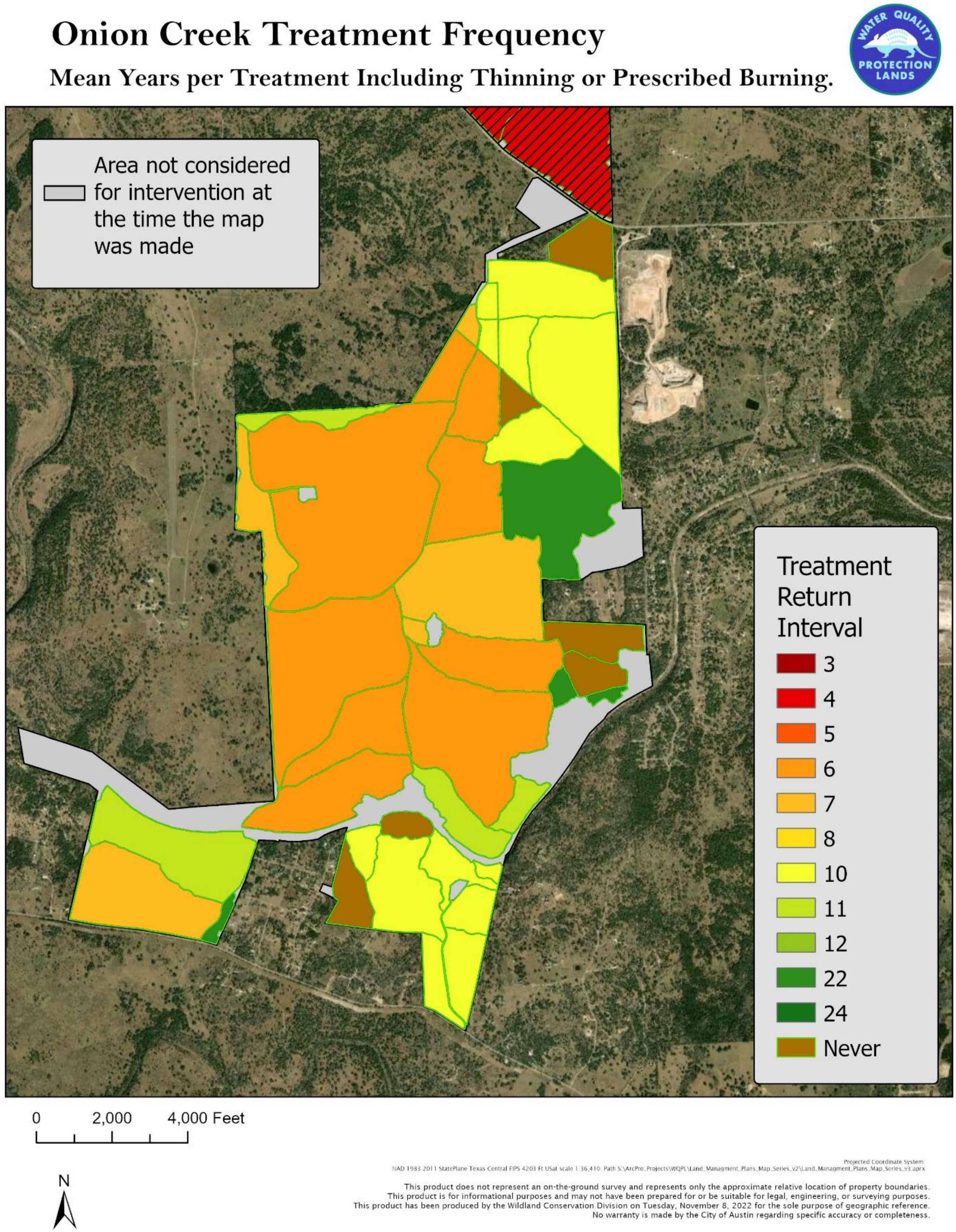

Figure 39: Treatment frequency map for Onion Creek management unit.

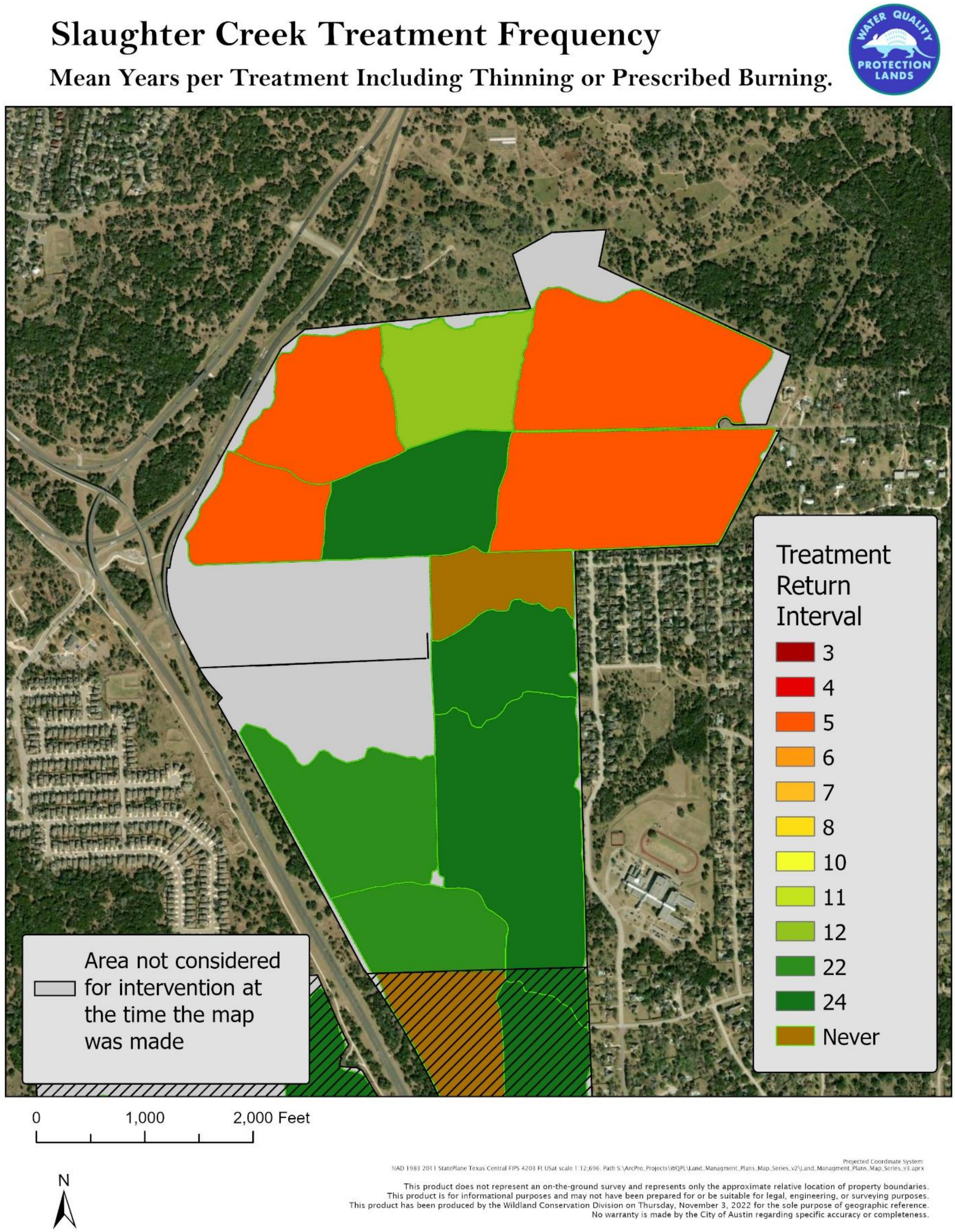

Figure 40: Treatment frequency map for Slaughter Creek management unit.

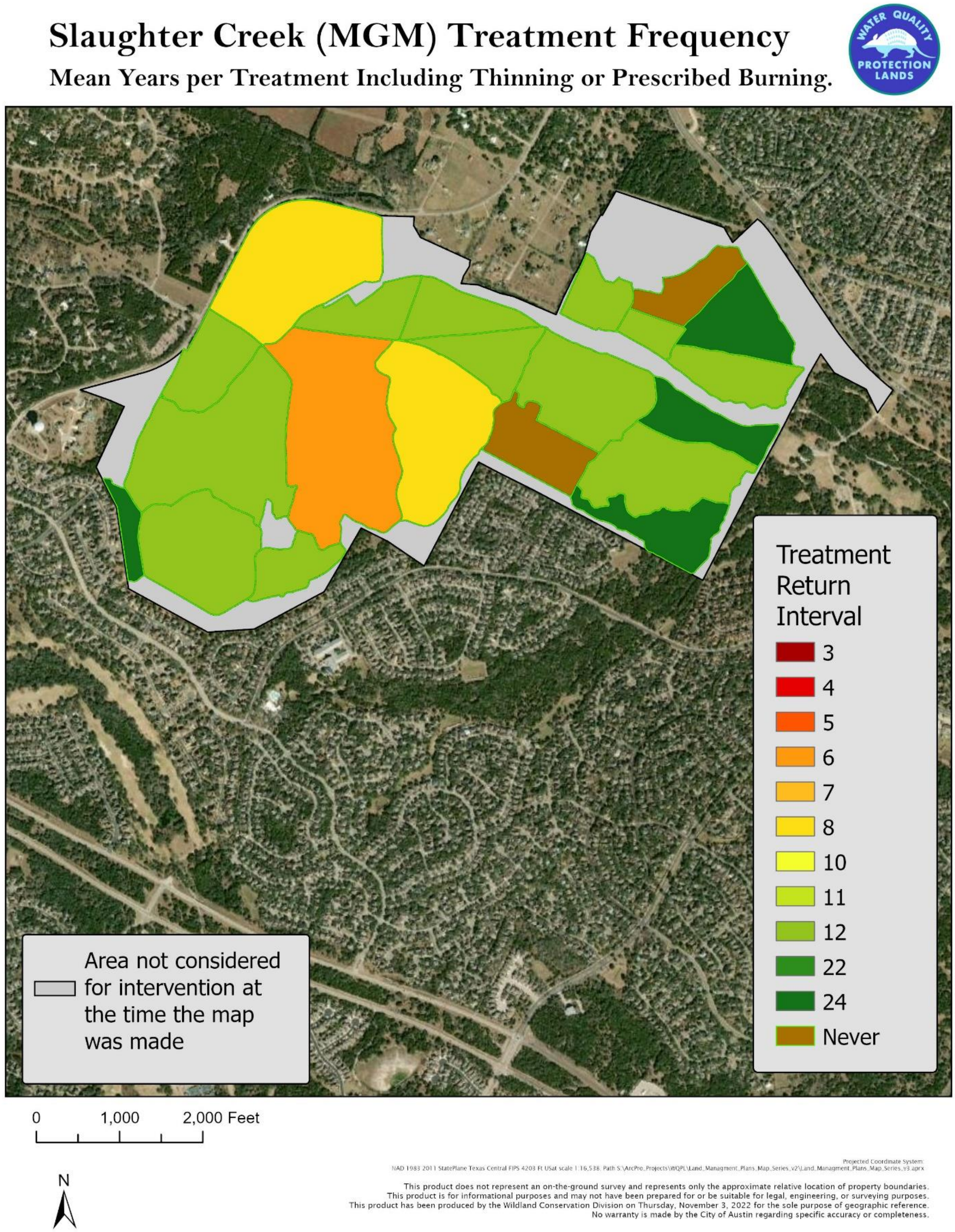

Figure 41: Treatment frequency map for Slaughter Creek (Mary Gay Maxwell) management unit.