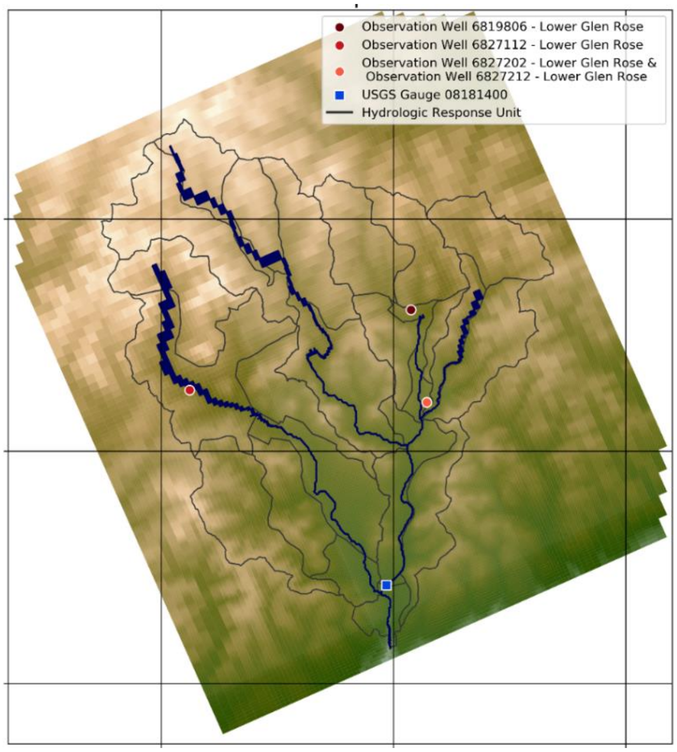
Comparative Evaluation of Wastewater Disposal Practices in the Contributing Zone of the Edwards Aquifer



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Executive Summary

The City of San Antonio Edwards Aquifer Protection Program (EAPP) was expanded when it was renewed in 2015 to provide funding for research and data acquisition on the Edwards Aquifer. As part of that program, Southwest Research Institute® (SwRI) was chosen to evaluate wastewater disposal in the recharge and contributing zones of the Edwards Aquifer using an integrated hydrologic model. The principal objective of the project was to compare the relative impact that different wastewater disposal facilities would have on the quality of water recharged to the Edwards Aquifer. Wastewater disposal facilities considered as part of the evaluation included on-site sewage facilities (OSSF), Texas Land Application Permit (TLAP), and Texas Pollutant Discharge Elimination Systems (TPDES).

A requirement of the EAPP research and data acquisition program was that funded projects must be located in Bexar County, Texas. Helotes Creek watershed, which is wholly contained in Bexar County, was selected as the study site for the SwRI project. Periphyton and sestonic sampling and analysis indicate that the current trophic state of the Helotes Creek watershed is oligotrophic and possibly slightly mesotrophic which suggests that the stream and watershed have been marginally impacted by wastewater discharges. An objective of the SwRI project is to determine the impact that different wastewater facility types would have on the trophic state of Helotes Creek watershed and the quality of water from the watershed that recharges the Edwards Aquifer.

Currently, OSSFs are the only type of wastewater disposal facility in the Helotes Creek watershed. Analysis of water samples from wells and surface-water bodies provide a measure of how the existing OSSFs have impacted local water quality. Numerical and analytical models were developed to estimate the impact that OSSF, TLAP, or TPDES wastewater facilities would have on water quality in Helotes Creek watershed and the quality of water from the watershed that recharges the Edwards Aquifer.

An integrated hydrologic model of Helotes Creek watershed was developed to generate surface-water/groundwater regimes of the study area. A transport model calculated transport rates and masses for different reservoirs predicated on flows simulated with the integrated hydrologic model. Total nitrogen was designated as the conservative constituent of interest in the transport simulations. These models were used to predict the impact to the quality of water recharged to the Edwards Aquifer from a variety of OSSF scenarios and from hypothetical TLAP and TPDES wastewater facilities in Helotes Creek watershed.

The integrated hydrologic model developed for Helotes Creek watershed incorporated all available information and data for the study site. Nonetheless, during development of the model, it became apparent that this information and data were insufficient to develop a robust comprehensive model of the study domain. Although this shortcoming limits the model when attempting to make detailed, high-resolution predictions of flow and transport in the Helotes Creek watershed, the model is shown to be useful and defensible when making comparative assessments in which the foundational conceptualizations are the same for the cases being compared.

A Base Case model was constructed to replicate, to the degree possible, mass loading from OSSFs currently present in Helotes Creek watershed. Mass loading for the Base Case was calculated using the transport model predicated on flows generated using the integrated hydrologic model. Mass loadings from eight alternative scenarios were then calculated using the same modeling assembly to evaluate the anticipated impact that various OSSF operational performances, a TPDES, and four different TLAP facilities within the Helotes Creek watershed would have on the quality of water recharged to the Edwards Aquifer.

Two locations in the watershed were considered for the location of the TLAPs, one in the less-developed upgradient northern portion of the watershed and one in the more-developed southern portion. The TPDES was placed in the southern portion of Helotes Creek watershed. OSSFs in the model were removed from the area proximal to the hypothetical wastewater disposal facilities. Mass loading from each TLAP system was predicated on the size of the land available at each site, 32 acres at the northern location and 13 acres at the southern location. Volumetric wastewater volumes discharged in the one TPDES and the four TLAP scenarios varied from 0.05 to 0.86 million gallons per day (MGD). Similarly, nitrogen loadings varied from 33.2 to 99.2 kg/d. Mass loadings assigned to the TLAP and TPDES facilities are consistent with comparably-sized facilities in Texas. Due to its greater acreage, mass loading disposal at the northern TLAP location (32 acres) was greater than loading at the southern location (13 acres), hence mass loading to recharge of the Edwards Aquifer was greater for scenarios that represented facilities at the northern location.

The size and capacity of the hypothesized wastewater facilities in the TLAP and TPDES scenarios were reasonable and consistent with possible residential development in the study area. Capacity of the TPDES and TLAP facilities was sufficient for upwards of 4,800 homes covering almost 1,800 acres. Residential developments of this size are conceivable within the 15,640 acres of the Helotes Creek watershed. Accordingly, the nitrogen mass load from the candidate wastewater disposal facilities represented in these scenarios recharges the Edwards Aquifer at rates that are reasonable for this size and capacity of wastewater disposal facility.

As expected, the mass load in water recharged to the Edwards Aquifer is dependent on the mass load discharged to the environment, regardless of the wastewater disposal facility type. Modeling of the Base Case and eight scenarios demonstrates that the relative impacts of OSSFs, TLAP Subsurface Area Drip Dispersal Systems (SADDS), TLAP Surface Spray/Irrigation systems (SS), and TPDES practices vary depending on disposal type, mass loading, and location of the facilities. The scenarios with greatest impact on cumulative mass load to recharge of the Edwards Aquifer were the large, northern TLAP SS facility and the TPDES facility located in the southern portion of the Helotes Creek watershed. Model simulations illustrated that all scenarios, with the exception of the modest-sized TLAP SADDS, resulted in higher cumulative mass loading to the water recharged to the Edwards Aquifer relative to the Base Case indicating that in cases of failure of OSSF systems or increased development requiring a TLAP or TPDES, increased impacts to the quality of recharge to the Edwards Aquifer are to be expected.

Transport simulations support the argument that if either a TLAP or TPDES facility were to be installed in the Helotes Creek watershed and that the cumulative amount of wastewater disposed was substantially increased, the trophic state of Helotes Creek would be further degraded and likely classified as mesotrophic or fully eutrophic. Although eight scenarios were considered in the current project, evaluation of additional scenarios could provide further insight into the impact from other possible wastewater disposal facility types, locations, or number of units. Now that a transport/flow model assembly is developed and available, it would be informative to apply the model to the Edwards Aquifer contributing and recharge zones outside of Bexar County experiencing similar development pressures. Having the ability to quantitatively calculate the impact of wastewater disposal facilities in terms of mass loading on rivers and streams would greatly enhance the ability of the: 1) City of San Antonio to measure the impact from protecting lands in the contributing and recharge zones as part of the EAPP; and 2) Texas Commission on Environmental Quality to evaluate the impact of wastewater disposal into rivers and streams in the Edwards Aquifer contributing and recharge zones as part of its permitting processes.

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1 Introduction

The Edwards Aquifer supplies water to over 2 million people and serves as the City of San Antonio's primary source of water. Given the aquifer's critical importance to human and environmental health and economic viability, the Edwards Aquifer Protection Program (EAPP) was created to study, protect, and improve water quality in the recharge and contributing zones of the San Antonio segment of the Edwards Aquifer. The EAPP was established in 2000 after voters approved the allocation of an 1/8 cent of the sales tax to purchase lands and conservation easements to protect recharge to the Edwards Aquifer with the goal of stemming development in these sensitive areas. This program became quite popular and was approved again in 2005, 2010, and 2015. As part of the program approved in 2015, $10 million was designated to fund research and collect data to help achieve the program's goals. The EAPP is managed and administered by the City of San Antonio, and the San Antonio River Authority (SARA) is the contracted administrator of the water quality projects component funding this study.

Southwest Research Institute (SwRI) was granted funding to study the impacts of different wastewater disposal methods on the Edwards Aquifer water quality within Bexar County. This report provides a summary of the findings and work completed as part of this EAPP-funded project.

1.1 Problem Statement and Scope

There are three main types of wastewater disposal facilities used in Texas (**Figure 1-1**): 1) On-Site Sewage Facilities (OSSFs), such as septic systems, 2) Texas Land Application Permit (TLAP) facilities, which distribute treated effluent via subsurface drip disposal or surface irrigation, and 3) Texas Pollutant Discharge Elimination Systems (TPDES), which are facilities in which effluent from treatment plants is permitted to be disposed into waterways. The goal of this project is to examine and compare impacts to the quality of water that is, or could hypothetically be, introduced to the Edwards Aquifer from each type of wastewater disposal facility.

A requirement of the EAPP research and data acquisition program was that funded projects must be located in Bexar, Texas. Helotes Creek watershed, which is wholly contained in Bexar County, was selected as the study site for the SwRI project (**Figure 1-2**). Currently, this region of Bexar County is a residential, suburban community and all wastewater disposal in the watershed is handled using OSSFs. Impact to the San Antonio segment of the Edwards Aquifer from wastewater disposal in the Helotes Creek watershed is examined for existing conditions as well as for eight hypothetical scenarios. These scenarios assess the impact of future development in the watershed as well as that of hypothetical unpermitted facilities, current malfunctioning facilities, and possible alternative wastewater disposal facilities such as TPDES and TLAP facilities.

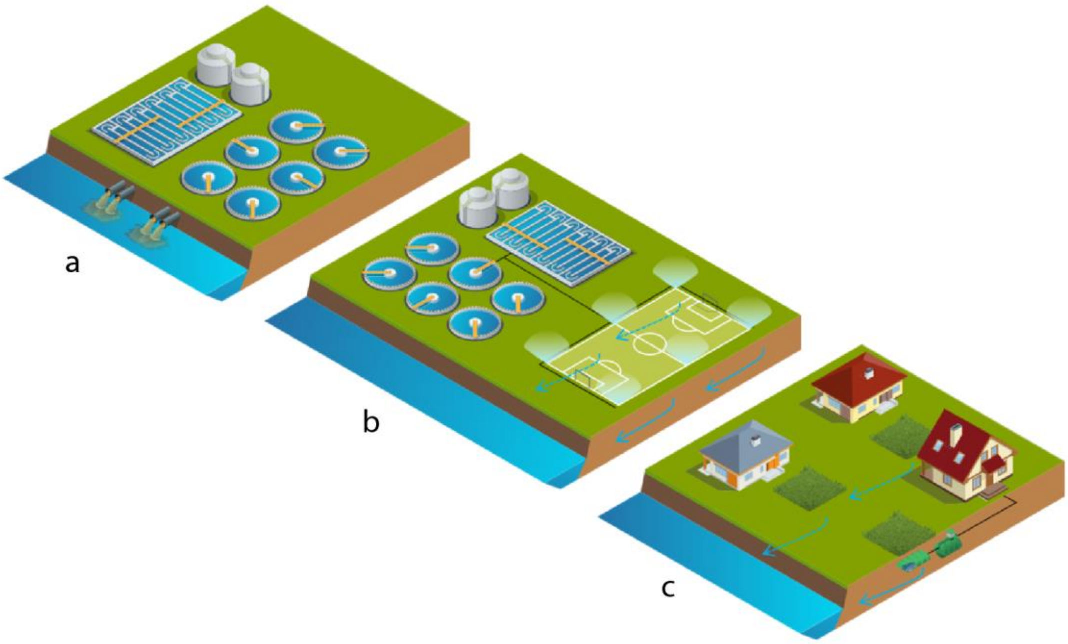


Figure 1-1 The three main types of wastewater disposal facilities in Texas: a) Texas Pollutant Discharge Elimination System (TPDES), b) Texas Land Application Permit (TLAP), and c) On-Site Sewage Facilities (OSSFs).

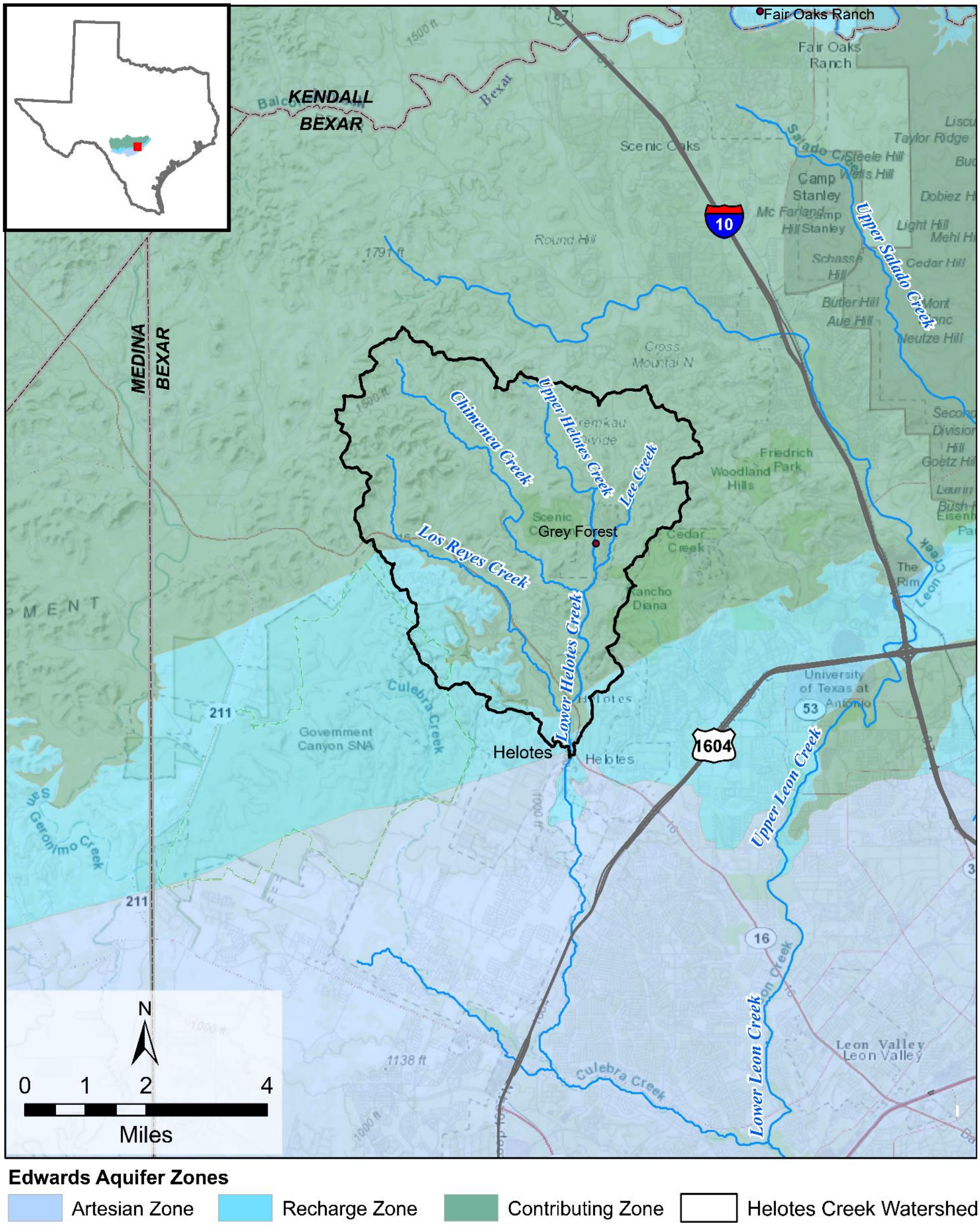


Figure 1-2 Helotes Creek watershed and the Edwards Aquifer in northwest Bexar County.

2 Study Area

2.1 Description of Helotes Creek watershed

The Helotes Creek watershed is located in northwestern Bexar County within the contributing and recharge zones of the San Antonio Segment of the Edwards Aquifer. It forms part of the Leon Creek watershed of the greater Medina River watershed (HUC 12100301), which is, in turn, a part of the northern San Antonio River watershed. The total area of the watershed is 15,680 acres (24.5 square miles). The Edwards Aquifer contributing zone comprises 13,696 acres (21.4 square miles) or 87.2 % of the Helotes Creek watershed (12.8% of the contributing zone of the San Antonio segment). The Edwards Aquifer recharge zone covers 1,984 acres (3.1 square miles) or 12.8% of the Helotes Creek watershed (0.26% of the recharge zone of the San Antonio segment) (**Figure 1-2**). The elevation ranges from 300 to 549 feet above sea level.

The watershed consists of five subwatersheds: Los Reyes Creek (5,888 acres (9.2 square miles)), Chimenea Creek (4,160 acres/6.5 square miles), Upper Helotes Creek (2,240 acres (3.5 square miles)), Lower Helotes Creek (1,536 acres (2.4 square miles)), and Lee Creek (5,760 acres (2.9 square miles)) (**Figure 2-1**).

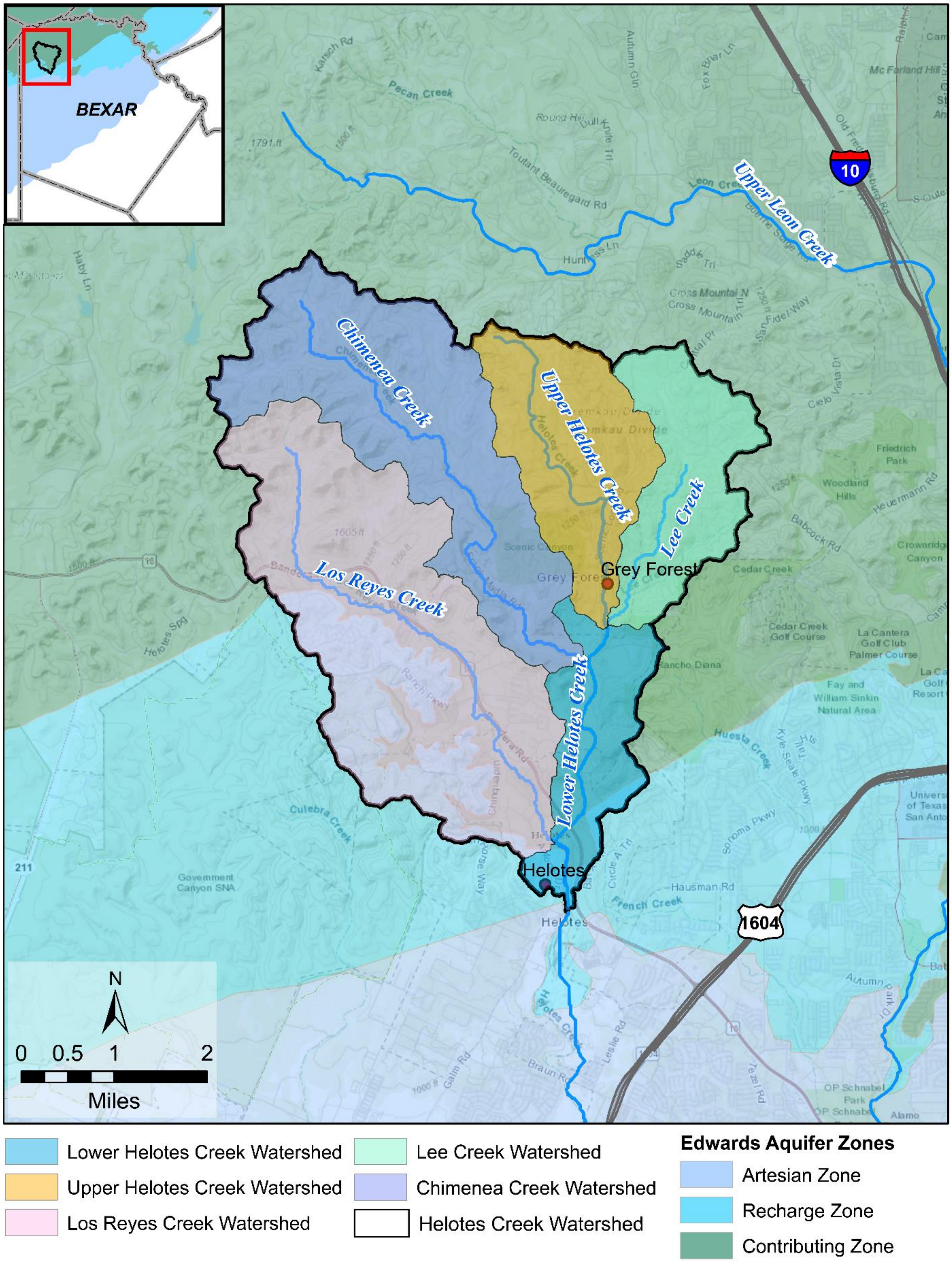


Figure 2-1 Subwatersheds within the Helotes Creek watershed.

2.2 Physiography and Climate

The Helotes Creek watershed study area is located in the Edwards Plateau Ecoregion, just north of the Texas Blackland Prairies Ecoregion which covers most of Bexar County (**Figure 2-2**). The Balcones Fault Zone serves as the divide between the north and south ecoregions. The Edwards Plateau Ecoregion is characterized by hilly, limestone dissected plateaus, karst topography, and juniper-oak savanna and mesquite-oak savanna. South of Haby Crossing Fault, and just south of the Helotes Creek watershed, the soils become finer grained and more clayey due to the presence of Cretaceous shale, chalk, and marl parent materials.

The watershed falls within the Subtropical Subhumid Climate Zone (**Figure 2-3**) as defined by Larkin and Bomar (1983). The subtropical climate is attributed to the transport of humid tropical air from the Gulf of Mexico, with air moisture decreasing from east to west as the humid tropical air contacts continental air masses coming from the north. This zone is characterized by hot summers and dry winters.

Table 2-1 shows the 30-year normals (1981-2010), both monthly and annual, for precipitation and temperature (PRISM Climate Group, 2020). The study area receives about 34 inches of precipitation a year with an average mean temperature of 67 °F.

Table 2-1 30-year climate averages in Helotes Creek watershed (PRISM Climate Group, 2020).

Month	Precipitation (inches)	Min Temperature (°F)	Mean Temperature (°F)	Max Temperature (°F)	Mean Dew Point Temperature (°F)
January	1.86	37.9	49.6	61.3	37.6
February	2.10	40.8	53.0	65.1	40.6
March	2.76	47.6	59.7	71.8	46.1
April	2.23	54.7	66.9	79.1	52.8
May	3.99	63.5	74.4	85.2	62.5
June	4.22	69.1	79.8	90.6	67.2
July	2.95	71.0	82.1	93.2	67.3
August	2.17	70.9	82.8	94.7	66.3
September	3.18	65.8	77.5	89.3	63.4
October	4.03	57.0	68.9	80.9	56.3
November	2.43	47.4	59.2	70.9	47.4
December	2.11	38.8	50.5	62.1	39.2
Annual	**34.03**	**55.4**	**67**	**78.7**	**53.9**

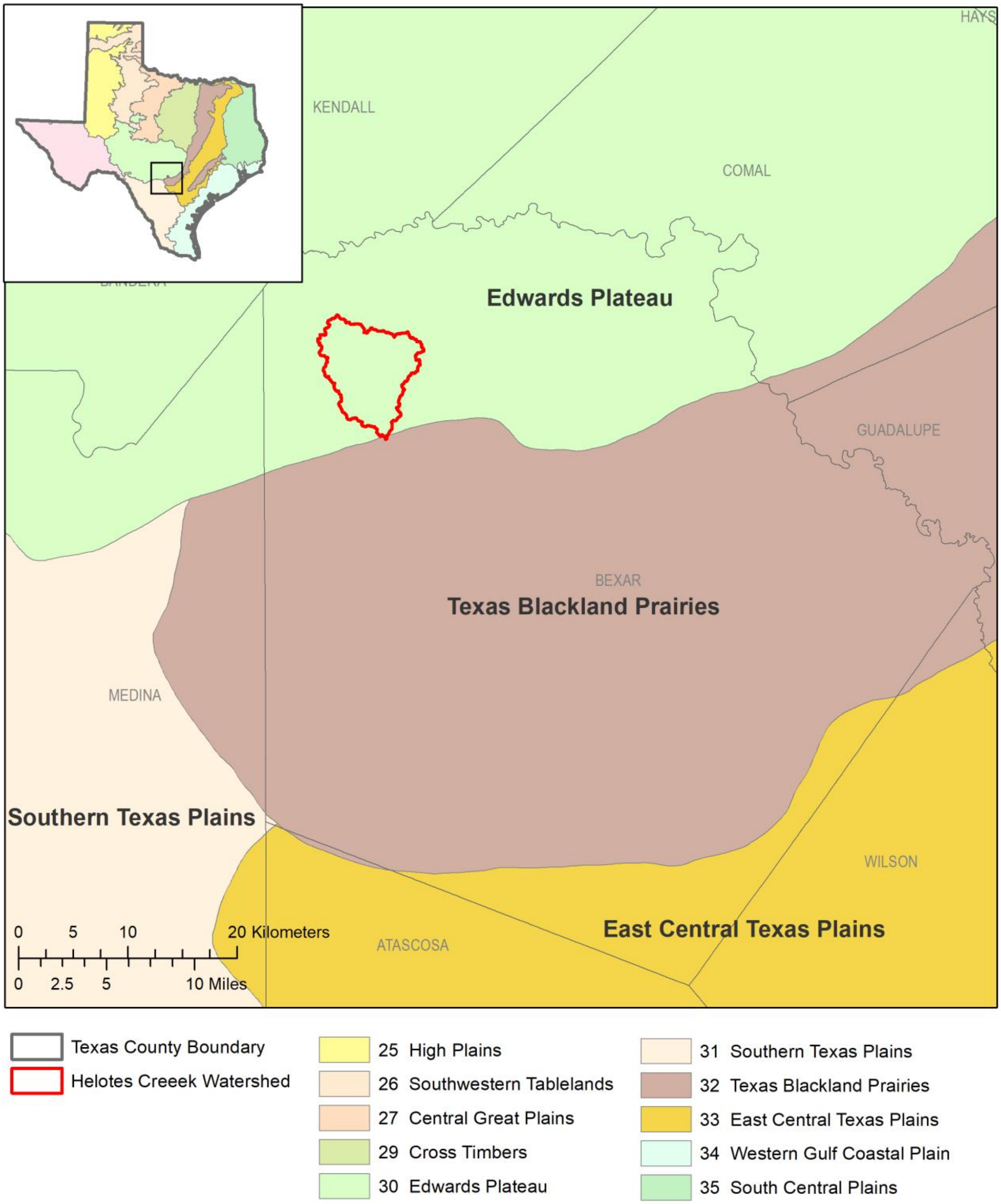


Figure 2-2 Ecoregions in Bexar County.

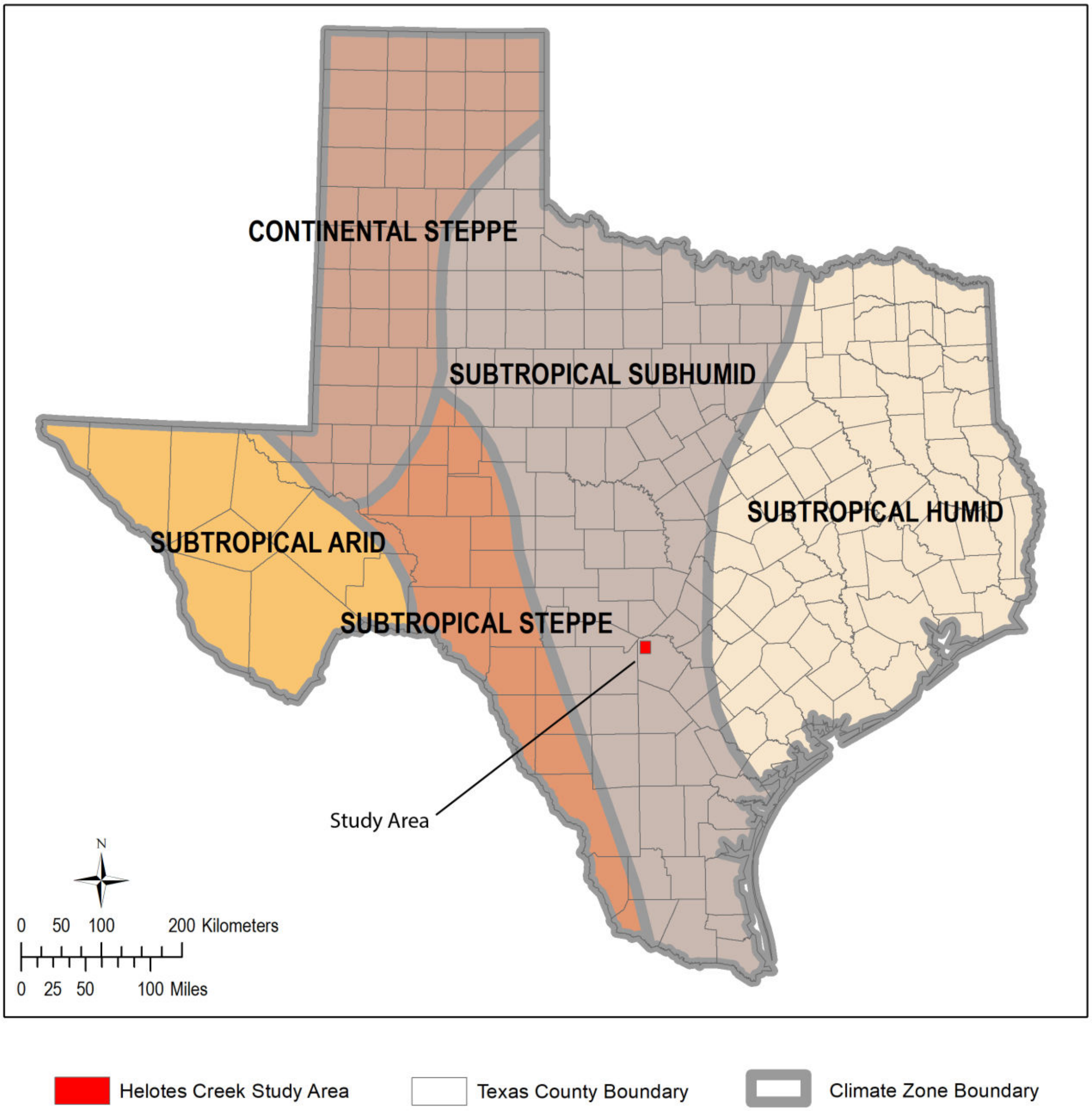


Figure 2-3 Texas climate zones from Larkin and Bomar (1983).

2.3 Hydrogeology

2.3.1 Hydrostratigraphy

Hydrostratigraphy of the study domain is dominated by the Edwards and Trinity aquifers, although younger hydrostratigraphic units are present to the south and outside of the area of focus. The Edwards and Trinity aquifers are karst aquifers consisting of lower Cretaceous limestone (Sharp, Green, & Schindel, 2019). The Trinity Aquifer is divided into lower, middle, and upper units based on lithology and hydraulic properties (Ashworth, 1983). The lower Trinity Aquifer includes the Sligo, Hosston, and Hammett Shale formations. The middle Trinity Aquifer includes the Cow Creek Limestone, Hensell Sand, and Lower Glen Rose Limestone. The upper Trinity Aquifer includes the Upper Glen Rose Limestone. The Edwards Aquifer overlies the Trinity Aquifer and comprises the Kainer, Person, and Georgetown formations.

Lithologic descriptions, water-bearing function, and thicknesses of hydrostratigraphic units (HSU) that comprise the Edwards and Trinity aquifers are provided in **Table 2-2**. From top to bottom, Maclay and Small (1976) delineated eight different hydrostratigraphic units (HSU) within the Georgetown (HSU I), Person (HSU II-IV), and Kainer (HSU V-VIII) formations of the Edwards Aquifer. Hydrostratigraphic units were defined based on lithologic characteristics (color, composition, texture) and hydrologic function. Highly permeable intervals are variably distributed throughout units II, III, and VI, with the most permeable parts of these units in honeycombed rock (Maclay, 1995; Lindgren et al., 2004). Groschen (1996) indicated that units III, VI, and VII transmit most of the ground water within the San Antonio region, although, highly permeable dissolution features are observed in all of the hydrostratigraphic units. Interaction between lithologies and structure has been observed to influence distribution of karst conduits (Hovorka et al., 1998). Ferrill and Morris (2003) and Ferrill et al. (2019) describe that lithology and structure interactions include refraction of normal faults controlled by failure angle differences between different mechanical layers. In such cases, more competent beds contain steeper normal faults segments that dilate during fault slip and subsequently localize groundwater flow and associated dissolution.

The Georgetown Formation (HSU I), which is included as the uppermost part of the Edwards Aquifer, is classified as a confining layer (Maclay & Small, 1976). Within the underlying Person Formation are the cyclic and marine member (HSU II) and the leached and collapsed member (HSU III), which are both classified as aquifers, and the underlying regional dense member (HSU IV), which is considered a confining unit. Within the underlying Kainer Formation, the grainstone (HSU V), Kirschberg evaporite (HSU VI), dolomitic (HSU-VII), and basal nodular members (HSU VIII) are classified as aquifers, although the basal nodular member may be a confining unit at localities where caves are absent.

Clark et al. (2016) subdivided the Trinity Aquifer into informal hydrostratigraphic units that crop out in northern Bexar and Comal counties (**Table 2-2**). The upper Trinity Aquifer – the Upper Glen Rose Limestone – is subdivided into six informal HSUs (ordered from top to bottom): cavernous, Camp Bullis, upper evaporite, fossiliferous (upper and lower), and lower evaporite. The middle Trinity Aquifer – the Lower Glen Rose Limestone – is informally subdivided into six HSUs (ordered from top to bottom): Bulverde, Little Blanco, Twin Sisters, Doeppenschmidt, Rust, and Honey Creek HSUs. The middle Trinity aquifer comprises the Hensell Sand, Cow Creek Limestone, and the Hammett Shale of the Pearsall Formation. The Hammett Shale is designated as the confining unit at the base of the model. The outcrop pattern of HSUs in the study area is illustrated in **Figure 2-4**, from the geologic framework model.

The cavernous, upper evaporite, the upper fossiliferous, and lower evaporite HSUs are considered as aquifers in the Upper Glen Rose Formation, whereas the Camp Bullis and lower fossiliferous HSUs are considered confining units. Within the Lower Glen Rose Formation, the Little Blanco, Doeppenschmidt, and Honey Creek HSUs are considered aquifers and the Bulverde, Twin Sisters, and Rust HSUs act as semi-confining layers. At the base of the middle Trinity Aquifer, the Hensell Sand HSU is considered as either an aquifer or a confining layer and the Cow Creek HSU is an aquifer. Lastly, the Hammett Shale HSU in the upper part of the lower Trinity Aquifer is a confining layer.

2.3.2 Geologic framework and structural controls

The Cretaceous Edwards and Trinity aquifer strata underwent regional-scale normal faulting during the Miocene epoch to form the Balcones Fault Zone (Hill & Vaughan, 1898; Weeks, 1945). The Balcones Fault Zone is the primary structural feature in the Edwards-Trinity Aquifer system and comprises a series of downthrown blocks that trend northeast to southwest within the study area. Its surface expression produces the Balcones Escarpment, a physiographic feature that separates the Edwards Plateau from the Gulf Coastal Plains.

Geologic structures, namely faults and fractures, can act as either barriers or conduits to flow depending on the associated porosity, cementation, and other deformation characteristics (e.g., clay smear). The permeability architecture of the aquifer system, described by Ferrill et al. (2005; 2010; 2019), is strongly controlled by geologic structures in three ways: (i) faults juxtapose permeable and impermeable units, (ii) structural thinning of aquifer strata, and (iii) faults create pathways, both laterally and vertically, for groundwater movement. These controls dictate how geologic structure influences groundwater flow. This study primarily relied upon the fault mapping of Clark et al. (2016), and implemented this structural control for the geologic framework and groundwater model. Clark et al. (2016) built on previous fault mapping in the region by Collins and Hovorka (Map No.18, 1997) and Collins (2000), among others. As described in **Section 2.3.3**, the fault displacements incorporated in the model are internally consistent with refined HSUs within the study domain.

Geologic structure strongly influences the hydrogeology of the study area. This geologic structure is dominated by normal faults of the Balcones Fault Zone, including the offset and juxtaposition of hydrostratigraphic units associated with these faults (Collins & Hovorka, 1997; Ferrill et al., 2004; Ferrill & Morris, 2008; Clark et al., 2016; Ferrill et al., 2019b). The faults typically have dips of 60 degrees or greater, depending upon the stratigraphic unit (Ferrill & Morris, 2008). The Haby Crossing Fault is the largest fault in the study domain in terms of displacement. Southwest of the study domain, the fault has a maximum throw of about 178 m (584 ft) and juxtaposes virtually the entire Edwards Aquifer stratigraphic section with rocks of the Glen Rose Formation (Ferrill et al, 2005).

Within the Helotes Creek watershed, the large offset north of Haby Crossing Fault has resulted in the removal of all Edwards units in the creek channel. The uppermost unit in the Trinity Aquifer, the Cavernous unit, is the unit exposed throughout most of the downstream portion of the Helotes Creek watershed (**Figure 2-4**). Remnants of the Edwards units north of Haby Crossing Fault are restricted to upland areas as evidenced by Edwards rocks only present as capping the Trinity units in the northern portion of the watershed. The Edwards units are above the water table and essentially dewatered with the possible exception of minor perching.

Multiple investigations support the interpretation that the upper 120-150 feet of the Trinity Aquifer is hydraulically connected with the lower Edwards Aquifer (Veni, 1994; Gary et al., 2011; Green et al., 2011). This portion of the Trinity Aquifer is referred to as Internal A (Veni, 1994). Hence, even though Edwards units are absent in Helotes Creek watershed north of Haby Crossing Fault, the Trinity Aquifer Cavernous unit is in hydraulic communication with the Edwards Aquifer.

The oddly shaped exposure of the Edwards units in the Helotes Creek watershed immediately south of Haby Crossing Fault is not natural (**Figure 2-1**). This exposure of the Edwards Aquifer is due to the removal of the overlying Del Rio Clay as part of mining operations at the Martin Marietta limestone quarry at this location. By virtue of the fact that this feature is down gradient and outside of the study area renders it non-consequential to this evaluation.

Groundwater flow within the central portion of the study domain and upgradient (northwest) from Haby Crossing Fault is influenced by relay-ramp structures. Relay ramps are geological structures that form as tilted panels of rock that transfer displacement between two overlapping sub-parallel (en echelon) faults (Twiss & Moores, 1992). Relay ramps themselves may provide lateral continuity and unbroken fluid pathways with aquifers from aquifer recharge areas into the artesian zone and within the artesian zones (Collins & Hovorka, 1997; Ferrill & Morris, 2001; Hunt, et al., 2015). Within a relay ramp, subsidiary normal faults and extension fractures commonly form that are oblique to the bounding faults and can influence groundwater movement (Grimshaw & Woodruff Jr., 1986; Collins & Hovorka, 1997; Ferrill & Morris, 2001). Fault zones themselves can also produce conduits or barriers to groundwater flow in the Trinity and Edwards aquifers (e.g. Maclay, 1995; Ferrill, et al., 2008); Ferrillet al., 2019b). This conduit versus barrier behavior is strongly influenced by lithology and mechanical character of rock layers during deformation, and the related deformation mechanisms, as well as the amount of displacement on the fault (e.g. Ferrill & Morris, 2008; Ferrill & Morris, 2003; Ferrill et al., 2019b). In the present study, because of the size of the model domain and lack of local control on fault zone permeability, specific permeability traits are not attributed to the faults. Instead, faults in the model simply represent surfaces across which hydrostratigraphic units are offset and juxtaposed with other units.

2.3.3 Interformational flow of the Edwards and Trinity aquifers

Informal subdivisions of HSUs, faults, and structural controls on groundwater movement offer better constraint on potential interformational flow between the Edwards and Trinity aquifers in the study area. The informal HSUs delineated by Clark et al. (2016) highlight transmissive HSUs (i.e., upper Person and Kainer of the Edwards Aquifer; cavernous, evaporite, and Honey Creek of the Trinity Aquifer) that are susceptible to lateral communication of juxtaposed transmissive units.

The Haby Crossing Fault is conceptualized to be the primary structural feature that allows interformational flow between the Edwards and Trinity aquifers in the study area (**Figure 2-5** and **Figure 2-6**). Throw of approximately 82 feet in the east and 492 feet in the west on the Haby Crossing Fault in the study area is sufficient to juxtapose permeable Edwards aquifer HSUs in the hanging wall of the fault against permeable HSUs of the Trinity Aquifer on the footwall of the fault. Specifically, the fault juxtaposes the cavernous HSU of the Trinity Aquifer on the upthrown side of the fault with the water-bearing HSUs in the Person and Kainer formations of the Edwards Aquifer on the downthrown side of the fault (**Figure 2-7**and **Figure 2-8**). Past work has shown that the Haby Crossing Fault and similar faults do not act as barriers to flow, but instead allow hydraulic communication and interaquifer groundwater flow paths across fault planes (Ferrill et al., 2005; Ferrill, et al., 2008; Johnsonet al., 2010; Saribudak & Hawkins, 2019). Previous studies suggest 60-100% of faulted Trinity units are in contact with the water-bearing HSUs in the Person and Kainer formations of the Edwards Aquifer along the Haby Crossing Fault (Ferrill et al., 2005).

The exact nature of the hydraulic relationship and interformational flow between the Edwards and Trinity aquifers at and downgradient from Haby Crossing Fault is therefore not well constrained. Uncertainty arises due to the fact that water that recharges the Cavernous unit north of Haby Crossing Fault may or may not pass through additional Trinity Aquifer units before arriving at the Edwards Aquifer. This flowpath is complicated by the karstic nature of both the Edwards and Trinity aquifers which introduces the potential for both diffuse- and conduit-flow mechanisms. The conceptualization embraced in this evaluation is that Haby Crossing Fault does not act as a barrier to flow and that virtually all water that discharges from the Helotes Creek watershed north of Haby Crossing Fault eventually recharges the Edwards Aquifer in close proximity to the study area. Hence, this conceptual uncertainty has minimal bearing on this evaluation due to the fact that all water discharged from the Helotes Creek watershed is assumed to eventually recharge the Edwards Aquifer.

Table 2-2 Hydrostratigraphic units in the study area.

Group or Formation	Formal and informal member	Hydrostratigraphic unit (HSU)	Map abbreviation	Description	Hydrologic function	Relative thickness (ft)	Model HSU
Taylor Group (Pecan Gap)		Upper Confining Units (UCU)	Kpg	Marl, calcareous clay, blue in the subsurface weathers greenish yellow	Confining		--
Austin Group			Ka	Massive, chalky, locally marly, mudstone, nodular wackestone, mudstone, nodular bioturbated wackestone	Confining, locally water bearing in cavernous zones	150-160	Austin
Eagle Ford Group			Kef	Brown, flaggy, sandy shale and argillaceous limestone, iron nodules	Confining		
Buda Limestone			Kb	Buff to light gray, dense nodular mudstone and wackestone, calcite-filled veins, bluish dendrites, iron nodules, iron staining	Confining	40-50	Buda
Del Rio Clay			Kdr	Fossiliferous blue-green to yellow-drown clay, packstone, iron nodules	Confining	40-50	Del Rio
Georgetown Formation		I	Kg	Porosity < 5%; dense, shaly limestone; mudstone and wackestone; isolated fossil molds	Confining	20-30	Georgetown
Person Formation	Cyclic and marine, undivided	II	Kpcm	Hard, dense, recrystallized limestone; mudstone; rudistid biomicrite; some moldic porosity	Aquifer	80-90	Upper Person
	Leached and collapsed	III	Kplc	Highest porosity within Person Formation (Maclay and Small, 1976); recrystallized, leached limestone; burrowed mudstone and wackestone; solution breccias	Aquifer	70-90	

Group or Formation	Formal and informal member	Hydrostratigraphic unit (HSU)	Map abbreviation	Description	Hydrologic function	Relative thickness (ft)	Model HSU
	Regional dense member	IV	Kprd	No water produced from this HSU (Maclay & Small, 1976); limestone, shaly to wispy, dense; mudstone; no open fractures	Confining	20-24	Lower Person
Kainer Formation	Grainstone	V	Kkg	Porosity < 10%; chalky to hard cemented miliolid grainstone with associated beds of mudstone and wackestone; locally honeycombed in burrowed beds	Aquifer	40-50	Kainer
	Kirschberg evaporite	VI	Kkke	Limestone and leached evaporitic rocks with boxwork porosity; most porous and permeable subdivision	Aquifer	40-50	
	Dolomitic	VII	Kkd	Porosity 5 – 20%; limestone, recrystallized from dolomite, honeycombed in a few burrowed beds; more cavernous in upper part	Aquifer	90-120	
	Basal nodular	VIII	Kkbn	Limestone, hard, dense; clayey mudstone to wackestone, nodular, wispy, stylolitic, mottled; isolated molds	Aquifer, confining unit in areas without caves	40-50	
Glen Rose Limestone	Upper Glen Rose Limestone	Cavernous	Kgrc	Limited lateral extent, is considered water-bearing and often hydrologically indistinguishable from the Edwards Aquifer; bedding planes, fractures, and caves, which allow meteoric water to infiltrate the Edwards Aquifer through juxtaposed units between the Trinity and Edwards aquifers	Aquifer	0-120	Cavernous

Group or Formation	Formal and informal member	Hydrostratigraphic unit (HSU)	Map abbreviation		Description	Hydrologic function	Relative thickness (ft)	Model HSU
		Camp Bullis	Kgrcb		Generally confining, although perched groundwater on less soluble beds transmitted laterally through caves and conduits	Confining	120-230	Camp Bullis
		Upper evaporite	Kgrue		Water bearing but not laterally continuous; diverts groundwater to discharge at springs and seeps (Clark, 2004; Clark et al., 2009)	Aquifer	88-210	Evaporite
		Upper Fossiliferous	Kgrf	Kgruf	Distinct from one another where biostrome exists between them; Kgrlf generally behaves as a confining unit, upper has numerous caves that enable groundwater transport over large distances.	Aquifer	0-40	Evaporite
		Lower Fossiliferous	Kgrf	Kgrlf		Confining	80-150	Evaporite
		Lower evaporite	Kgrle		Characteristically similar to Kgrue in water bearing function and contribution to spring discharge and seeps	Aquifer	8-10	Evaporite
	Lower Glen Rose Limestone	Bulverde	Kgrb		Semi-confining unit; water restricted to move laterally to springs and seeps by shale bed at top of unit	Semi-confining	30-40	Lower Glen Rose
	Lower Glen Rose Limestone	Little Blanco	Kgrlb		Interconnected porosity enables water-bearing unit to transmit water through caves and underground streams	Aquifer	30-40	Lower Glen Rose
	Lower Glen Rose Limestone	Twin Sisters	Kgrts		Semi-confining unit; water restricted to move laterally to springs and seeps along hillsides by shale beds	Semi-confining	10-66	Lower Glen Rose
	Lower Glen Rose Limestone	Doeppenschmidt	Kgrd		Characterized by bedding plane,	Aquifer	40-80	Lower Glen Rose

Group or Formation	Formal and informal member	Hydrostratigraphic unit (HSU)	Map abbreviation	Description	Hydrologic function	Relative thickness (ft)	Model HSU
				fracture, and cave porosity			
		Rust	Kgrr	Semi-confining in areas without faulting; near faults, characterized by caves (often linked to cave formation in the overlying Doeppenschmidt) and conduit porosity	Semi-confining	40-70	
		Honey Creek	Kgrhc	Transmissivity most characteristic of the lower half of this HSU; karstic features development favored by preceding biogenic porosity	Aquifer	45-60	Honey Creek
Pearsall Formation	Hensell Sand	Hensell	Kheh	Water-bearing in the northwest and grades into the lower member of the Glen Rose Limestone to the south becoming dolomitic and confining	Aquifer and confining	0-61	Hensell
	Cow Creek Limestone	Cow Creek	Kcccc	Very fine to fine-grained carbonate sand (grainstone) with localized crossbedding; recharged by losing streams where surface expression exists, and interformational flow with Hensell HSU; primary source of water production from the Middle Trinity Aquifer	Aquifer	40-72	--
	Hammett Shale	Hammett	Khah	Does not crop out in study area; Upper: claystone, with siltstone lenses, overlain by fossiliferous dolomitic limestone Lower: siltstone and dolomitic limestone	Confining	50	--

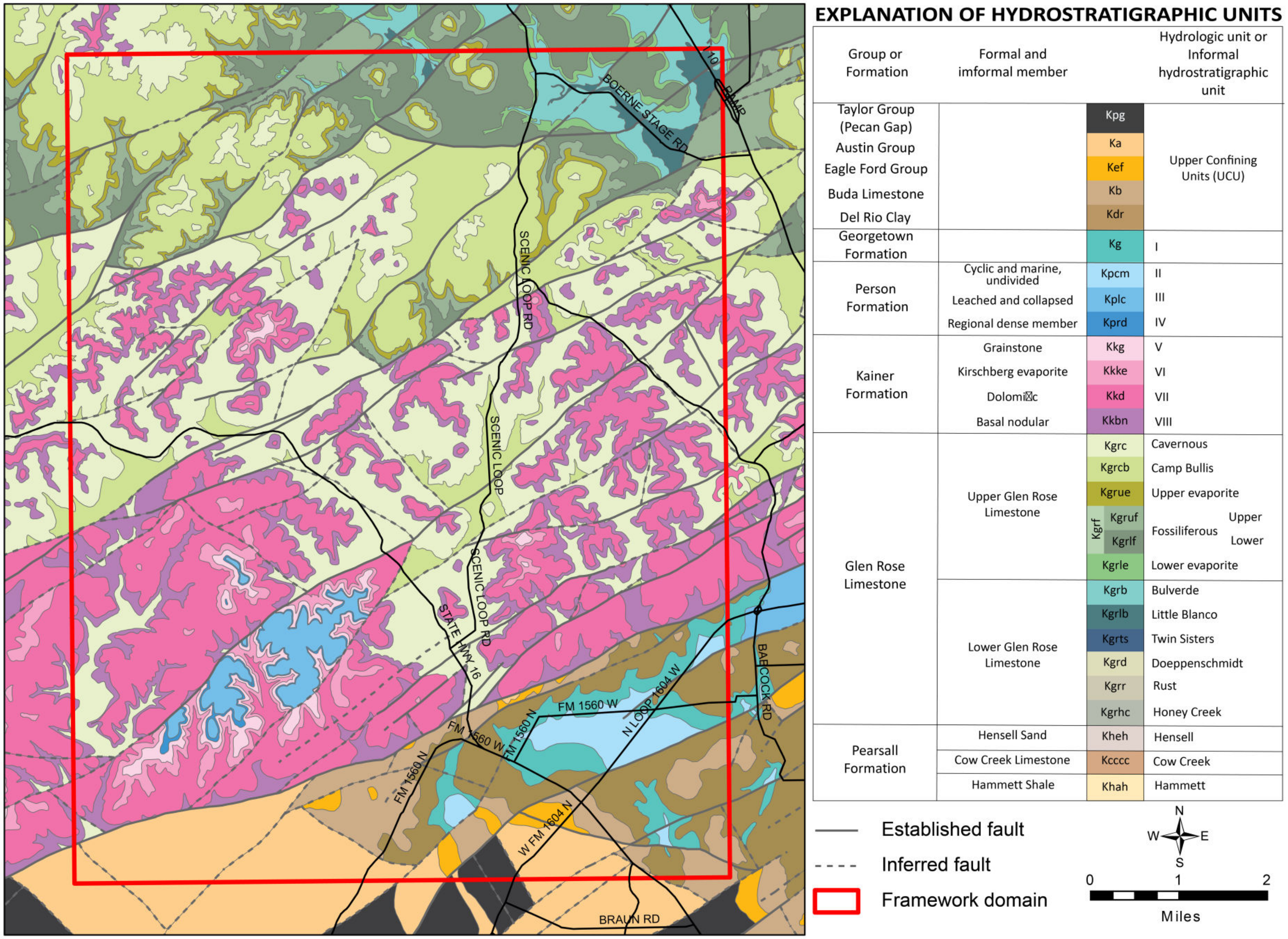


Figure 2-4 Outcrop geology and faults in the study area (modified from Clark et al., 2016).

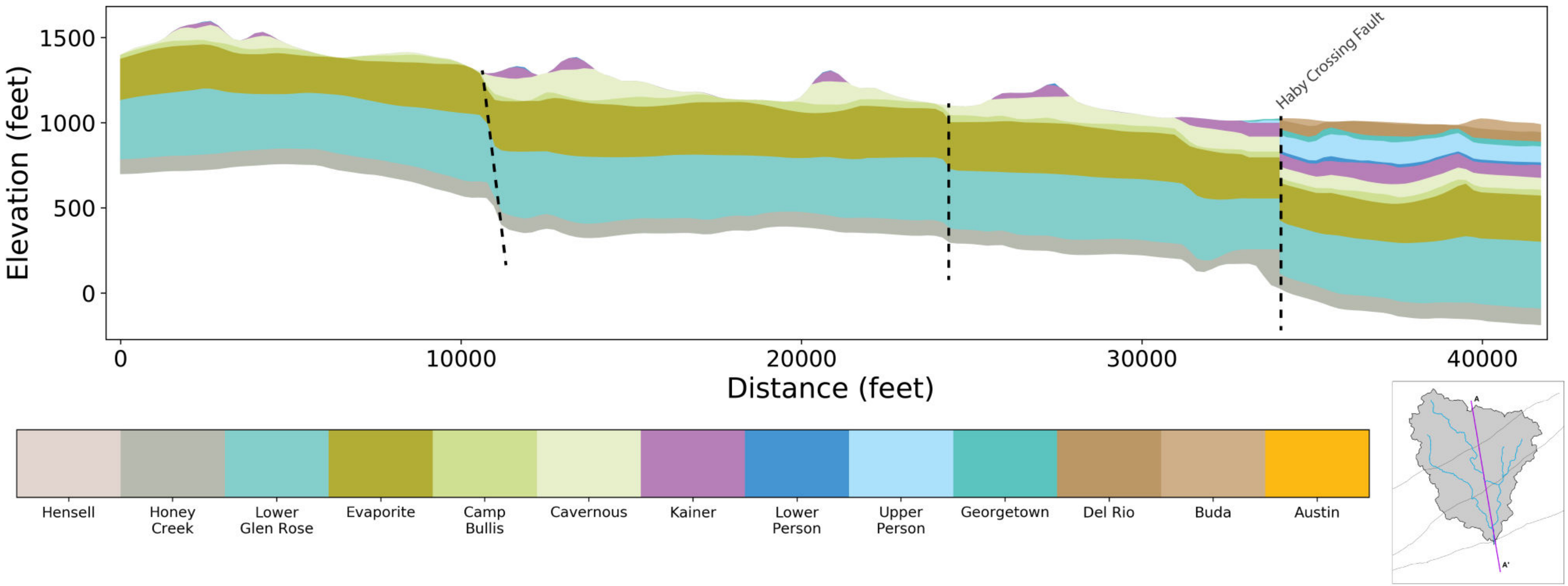


Figure 2-5 Cross section of HSUs within the Helotes Creek watershed. Vertical exaggeration = 5×.

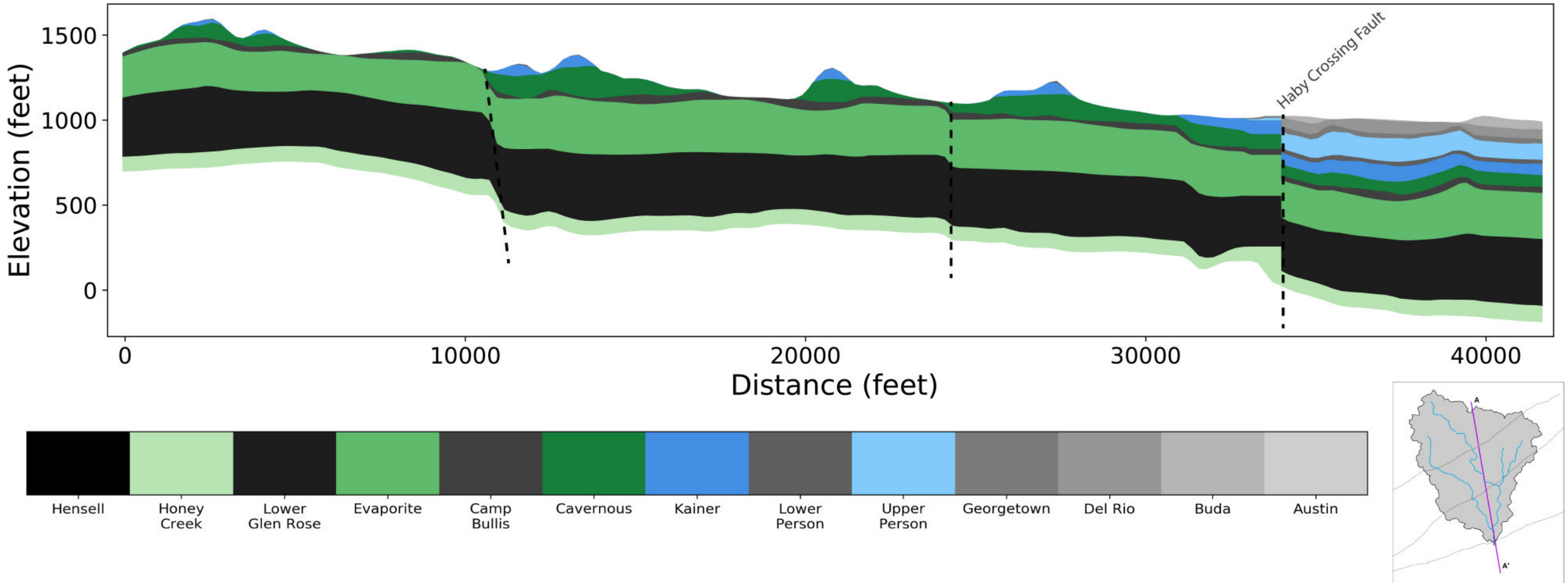


Figure 2-6 Cross section of transmissivity of HSUs within the Helotes Creek watershed.

Variations of gray and black represent low transmissivity, whereas shades of blue represent transmissive units of the Edwards Aquifer and shade of green represent transmissive units of the Trinity Aquifer. Vertical exaggeration = 5×.

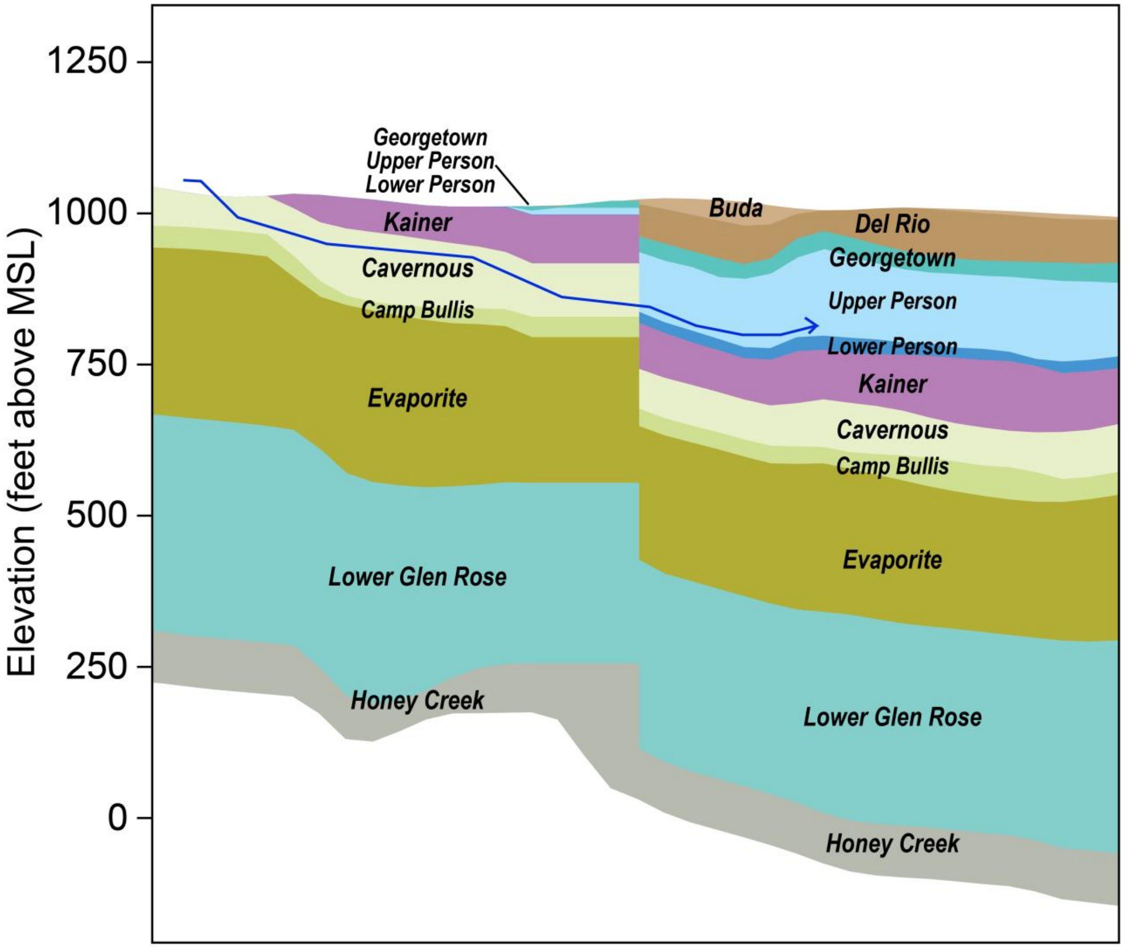


Figure 2-7 Juxtaposition of Edwards and Trinity hydrostratigraphic units along the Haby Crossing Fault from the cross section in Figure 2-5. Fault displacement is approximately 200 feet.

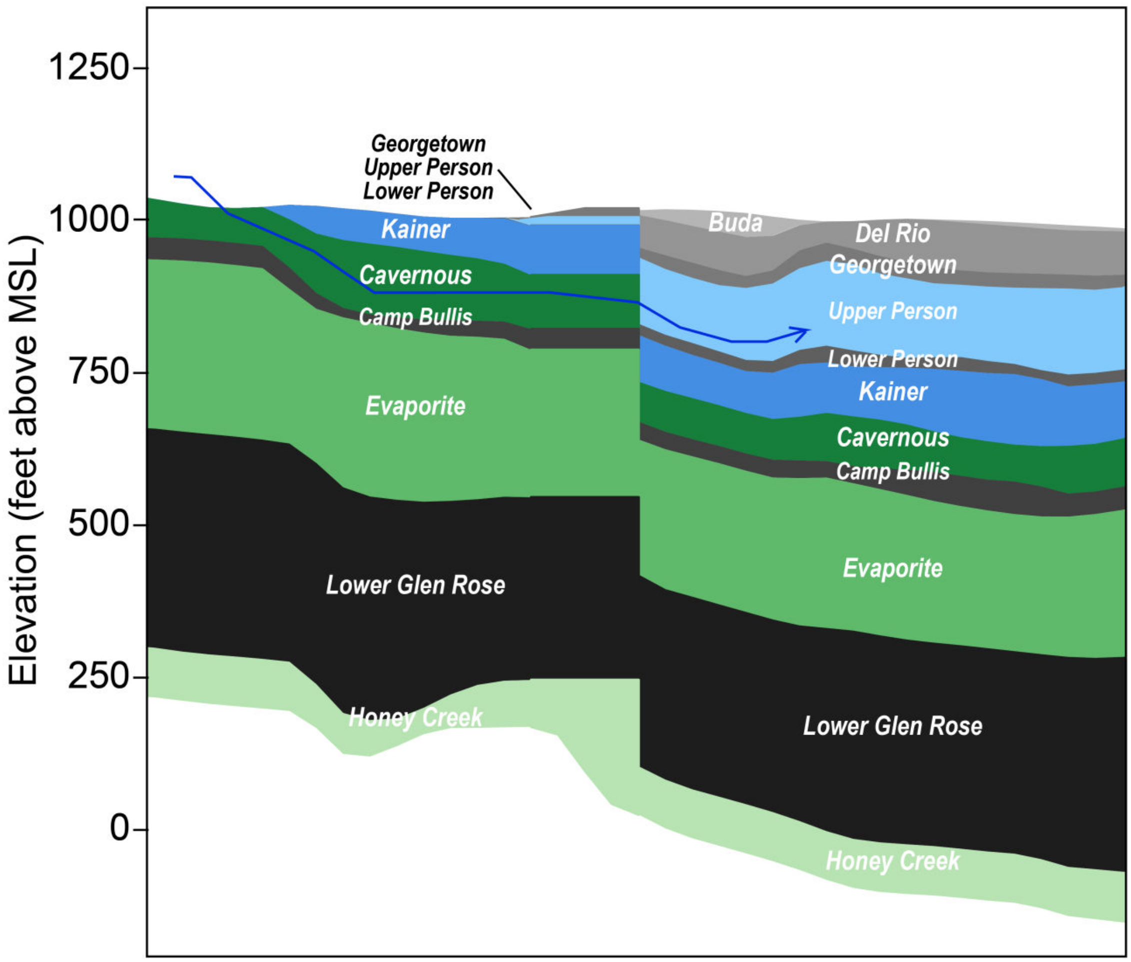


Figure 2-8 Juxtaposition of Edwards and Trinity transmissive units along the Haby Crossing Fault from the cross section in Figure 2-6. Fault displacement is approximately 200 feet.

2.4 Development

The Helotes Creek watershed includes the City of Grey Forest as well as part of the City of Helotes (**Figure 2-9**). In the 1800s, the area was a farming community consisting primarily of ranches, some of which in the northern portion of the watershed remain intact. The opening of the John T. Floore County Store in 1946 marked the start of commercial and economic growth in the area (Helotes, 2020).

This region is considered the fastest growing in Bexar County. The population of Helotes has grown from 1,535 in 1990 to 7,341 in 2010 according to the US Decennial Census. It currently is estimated to be home to 9,567 residents. Grey Forest currently has a population of about 500 residents (Grey Forest, 2020).

The Helotes City Master Plan (2009) encourages nodal type growth, or development in select places rather than sprawling strip mall style development. While impervious cover in the nodes may reach up to 70%, the overall percent of impervious cover will remain low. Densified "nodal" development areas are intended to decrease the overall impact on the environment and watershed (Helotes Planning and Zoning Commission, 2009).

Data from Bexar County Appraisal District (BCAD) illustrates the increase in development in the watershed. **Figure 2-10** shows yearly increase in residential development according to date of house construction. The plot shows the cumulative number of houses that has been built from 1840 to 2018. Exponential growth in the number of residences reflects the increase in population, which has been accompanied by commercial and economic development in the area.

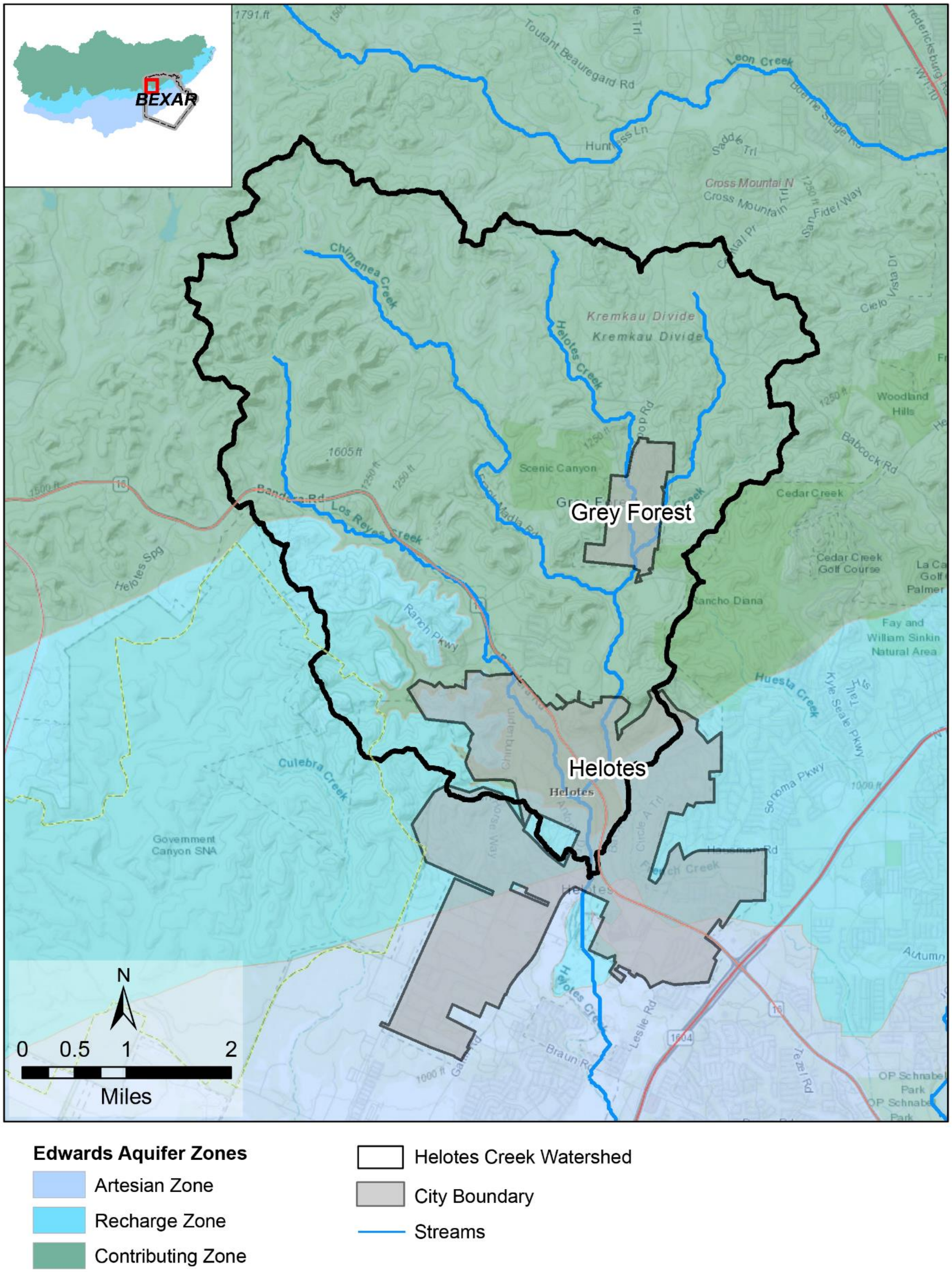


Figure 2-9 Map shows the extent of the City of Helotes and the City of Grey Forest with respect to the Helotes Creek watershed.

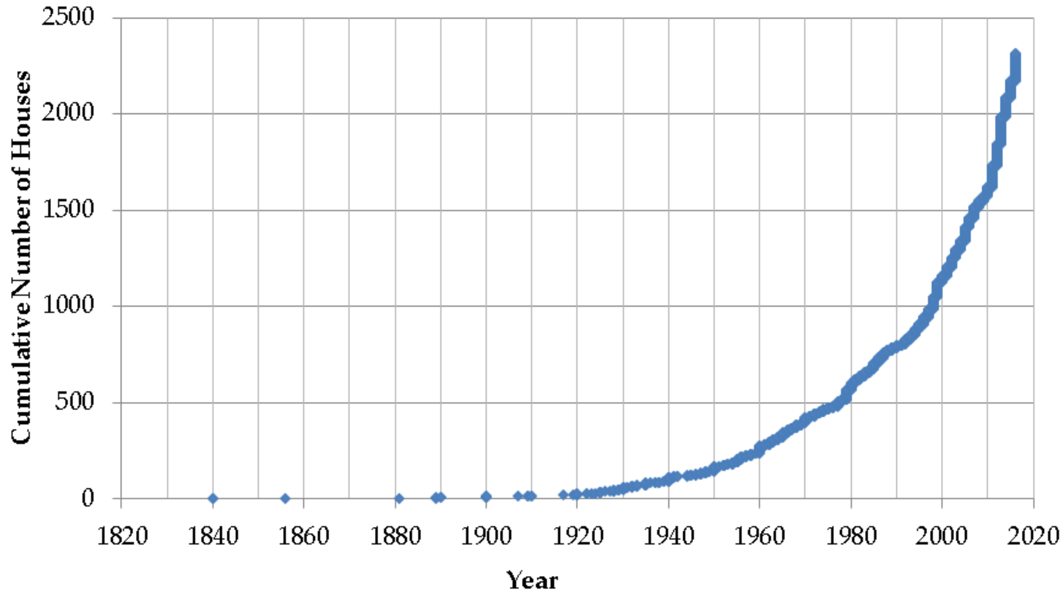


Figure 2-10 Total number of houses that have been built in the Helotes Creek watershed by year.

2.5 Data Collection

Numerous datasets were acquired for this study. Full records of data summarized in this section can be found in Appendix B.

2.5.1 Precipitation and Temperature

Daily precipitation and temperature datasets were acquired from PRISM Climate Group, which provides modeled climate data for the conterminous United States (PRISM Climate Group, 2020). The data are provided at a spatial resolution of 4 square kilometers. While 7 of these 4-km grid cells intersect the watershed, the grid cell that contained the watershed centroid was used as the variation among grid cells was minimal. Data was acquired for the timeframe 01-01-2000 to 09-30-2019. Data included precipitation, minimum, mean, and maximum temperature, and dew point temperature. These values were used as daily inputs for the Precipitation-Runoff Modeling System (PRMS) model. See Appendix B for data processing details.

2.5.2 Streamflow

Streamflow data were acquired from the USGS for Helotes Creek gage 08181400, located at 29°34'42"N, 98°41'29" W (**Figure 2-11)** (U.S. Geologic Survey, 2019)**.** Discharge is available for nearly 30 years, from 12-18-1991 to present. Measurements were recorded every 15 minutes in units of cubic feet per second. Discharge values were used for automated calibration of the standalone PRMS-IV model, manual and automated calibration of the integrated GSFLOW II model and as input to the mixing cell model.

Figure 2-12 shows a hydrograph for the years 1992 to 2019. Time series of annual peak flow at the gage for 1992 through 2019 are shown in **Figure 2-13.** The years with the highest recorded peak discharge in descending order are 1998, 2002, 2007, 2015 and 2018. **Figure 2-14** is a rating curve showing peak annual flow as compared to the recurrence interval. **Figure 2-15** shows daily average discharge at the gage with monthly average precipitation depths from the 4-km gridded precipitation dataset obtained from the PRISM Climate Group.

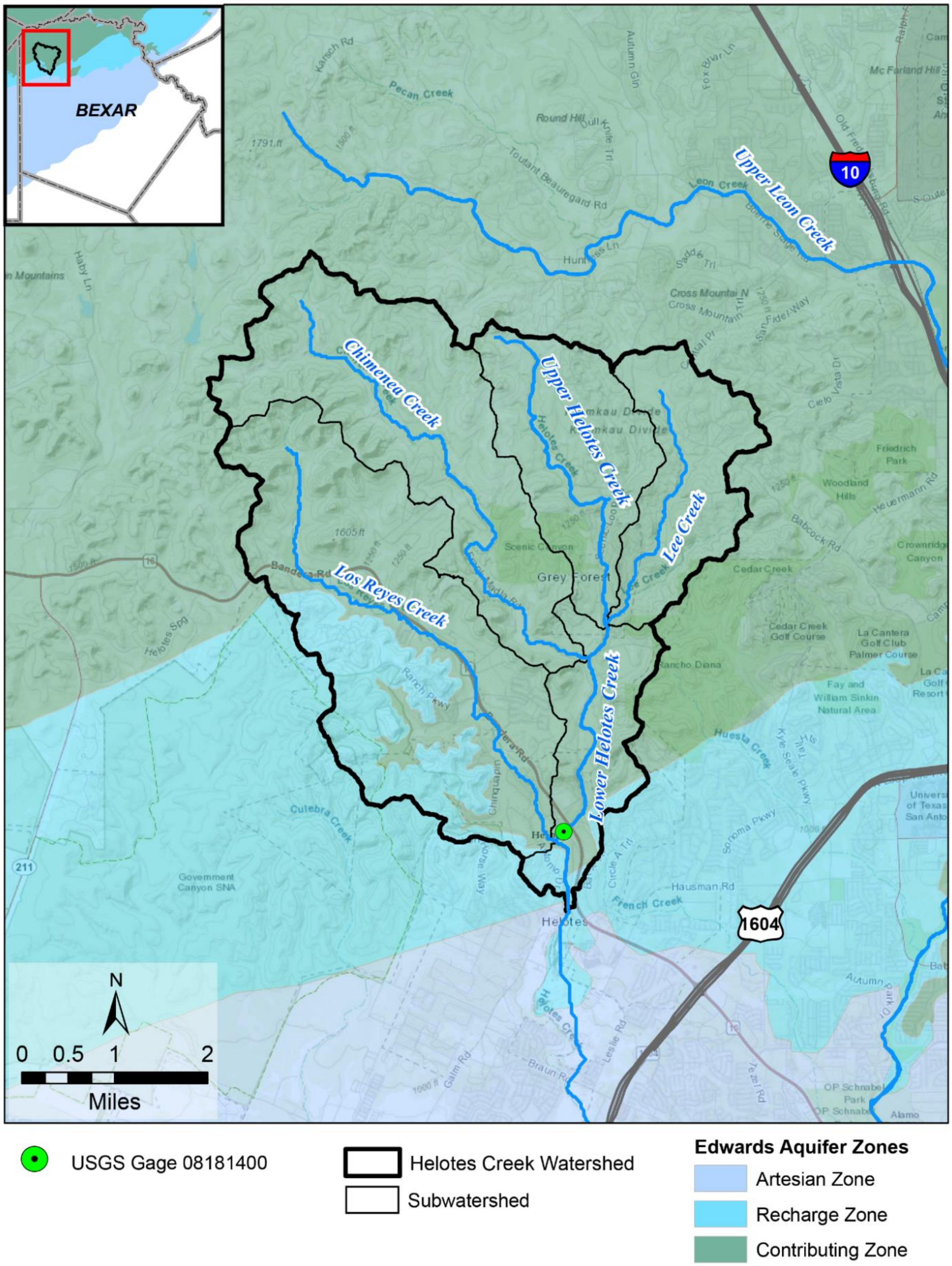


Figure 2-11 Map showing location of USGS gage 08181400 at Helotes Creek.

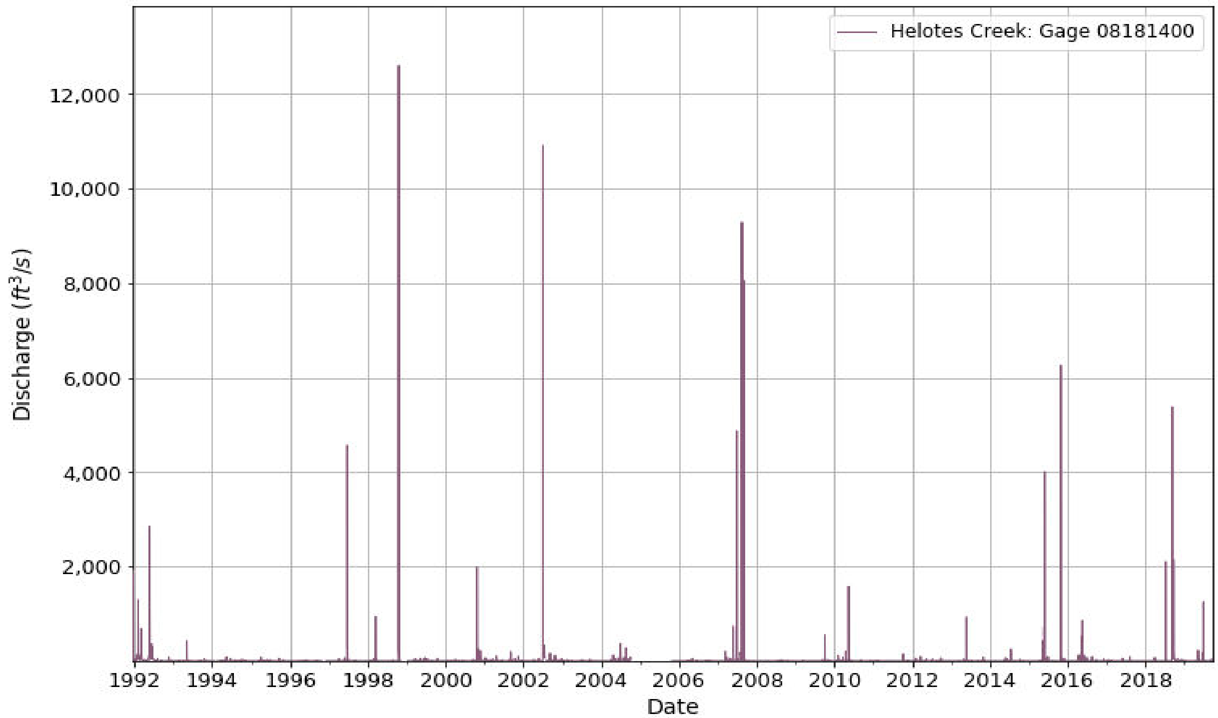


Figure 2-12 Discharge data collected from USGS Helotes Creek gage for 1992-2019.

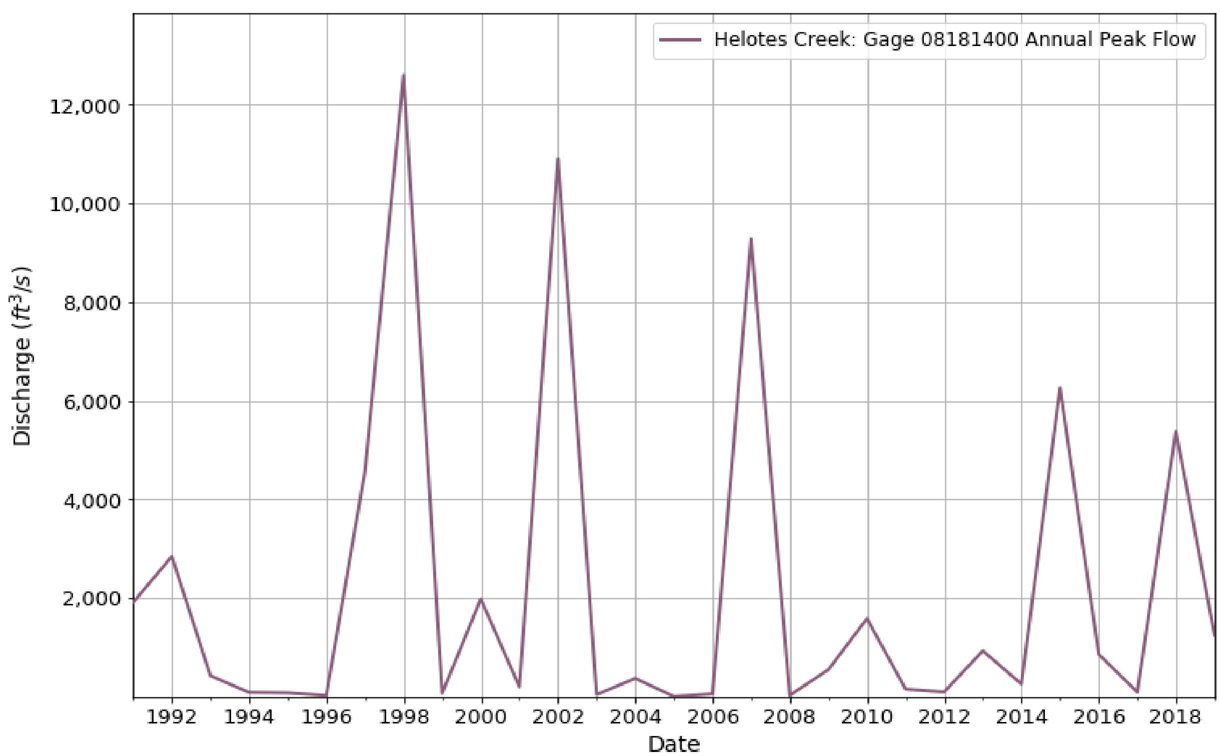


Figure 2-13 Annual average peak discharge at Helotes Creek gage for 1992-2019.

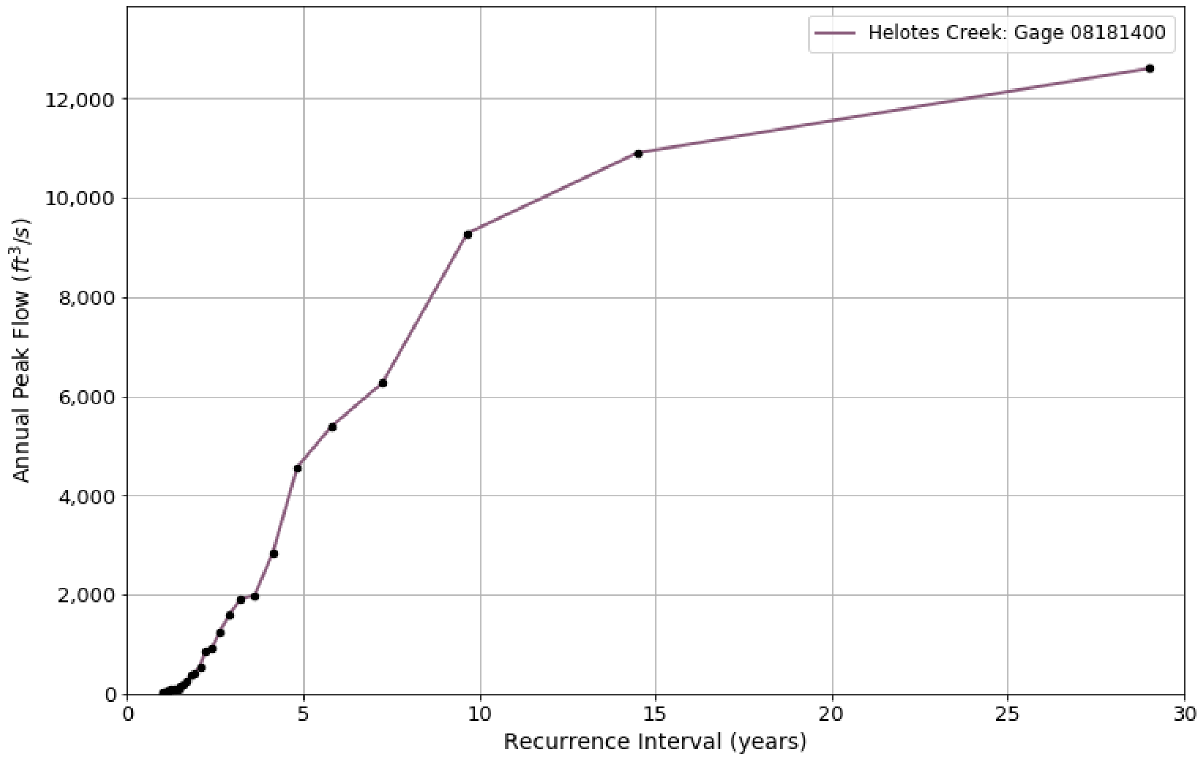


Figure 2-14 Reccurance interval created from the data collected at Helotes Creek gage.

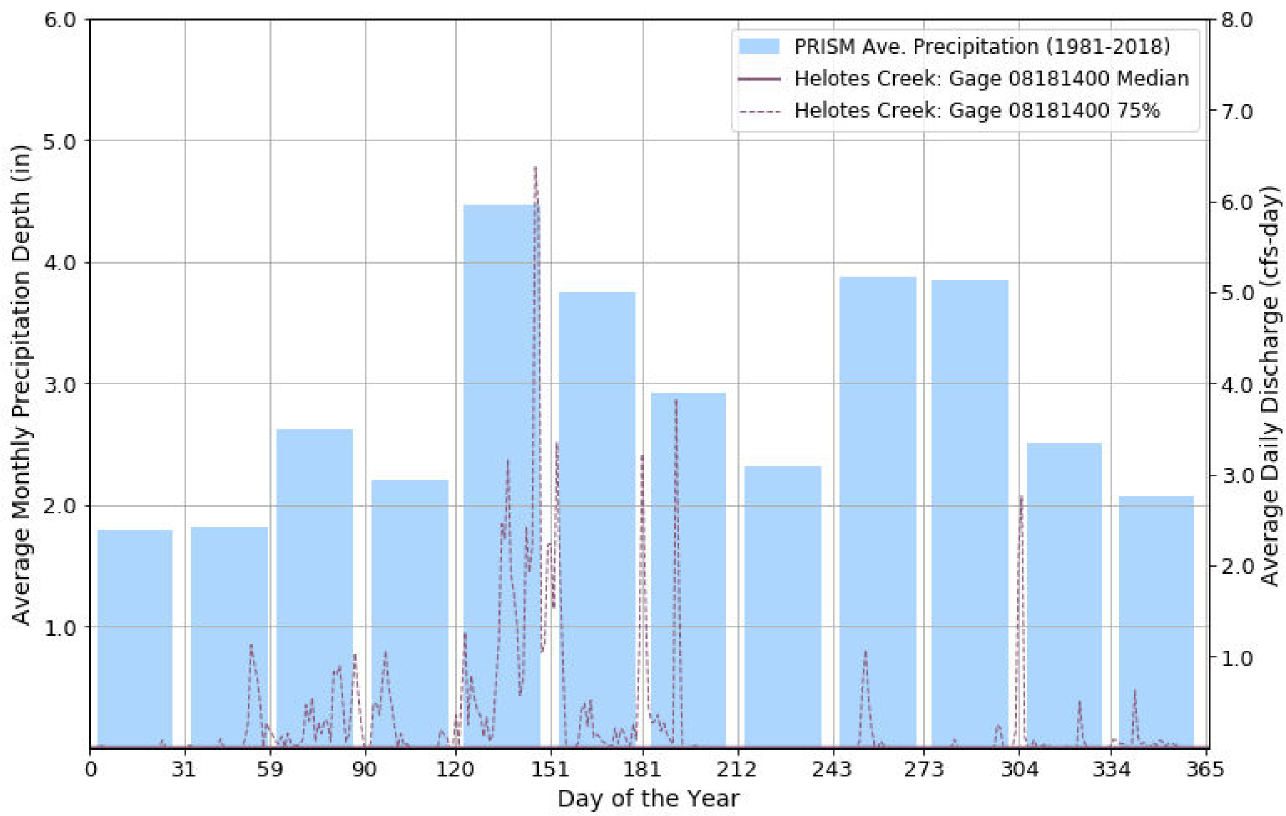


Figure 2-15 Average daily discharge as compared to the average monthly precipiation at Helotes Creek gage.

2.5.3 Digital Elevation Model

SARA provided digital elevation model (DEM) grid data at 1-m resolution in the spatial coordinate system of North American datum of 1983 (NAD 83) Universal Transverse Mercator (UTM) Zone 14N. Fugro was contracted by Texas Natural Resources Information System (TNRIS) to develop the DEM's from airborne LiDAR data collected in 2017. The DEMs were provided as square mile sized tiles and stitched together using mosaicking tools in ArcGIS. The tiles cover the expanse of the Helotes Creek watershed but do not include the northwestern corner of the study area (**Figure 2-16).** The DEM was used to delineate subwatersheds within the Helotes Creek watershed.

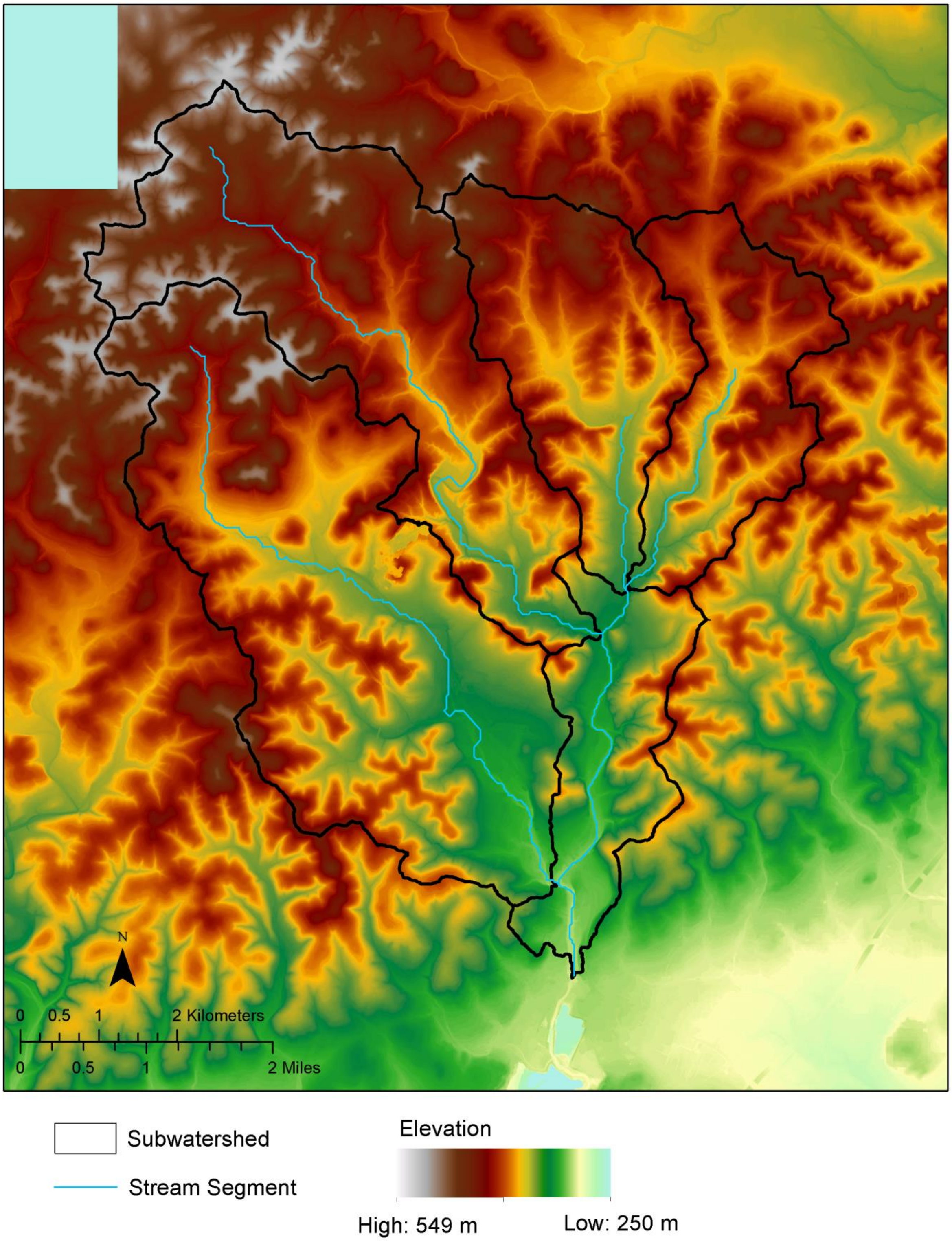


Figure 2-16 DEM of Helotes Creek watershed study area created from series of smaller rasters.

2.5.4 Wells and Water Levels

Well and water level data were acquired from the Texas Water Development Board (TWDB) databases. Freshwater-well data, including water-level measurements and associated well reports, and water chemistry information, were gathered from the TWDB Groundwater database. A total of 173 freshwater wells within the model domain and several additional wells just outside of the model domain were included in the study. Data acquired from the TWDB Brackish Resources Aquifer Characterization System (BRACS) database included geophysical well logs, water levels, and, in some cases, geochemical data. There are 5 reported brackish water wells within the study domain. In addition, the TWDB Submitted Driller Report, or SDR, database was queried for information regarding active and plugged wells along with their associated reports, where available. This effort yielded approximately 330 active and plugged well reports from the SDR database within the model domain (**Figure 2-17**).

Regional potentiometric surface maps from Toll et al. (2018) were used to inform conceptualizations in the study area with respect to the direction of regional groundwater flow. Lack of sufficient well-water level measurements within and around the Helotes Creek watershed prevented the creation of a more localized potentiometric surface. Well- and water-level data provided by the Trinity Glen Rose Groundwater Conservation District and Medina County Groundwater Conservation District were too sparse to sufficiently augment the existing database to support development of a localized potentiometric surface for the Helotes Creek watershed.

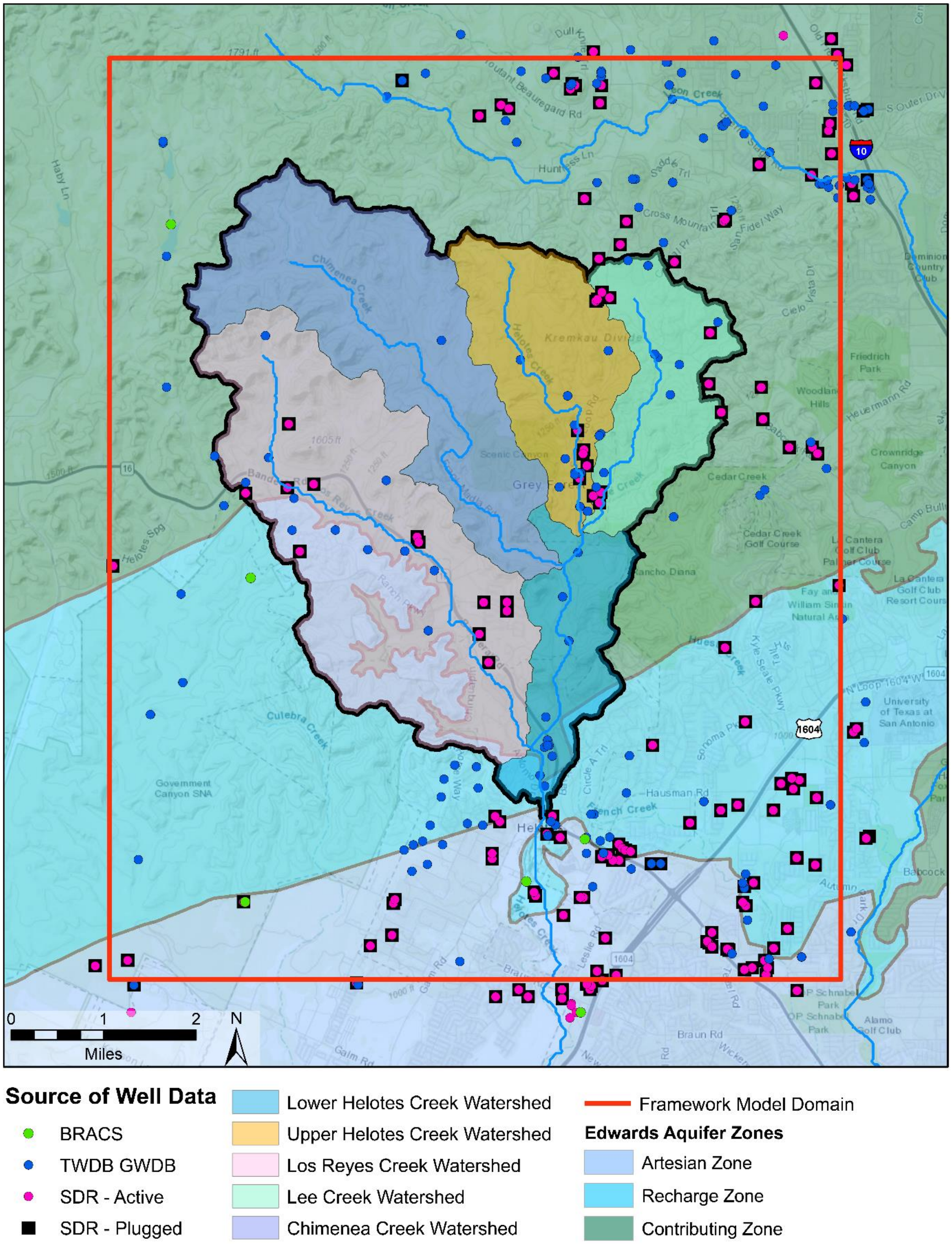


Figure 2-17 Sources of well and water level data in the study area.

2.5.5 Wastewater Treatment

2.5.5.1 OSSFs

The Texas Commission on Environmental Quality (TCEQ) is the primary permitting authority for OSSFs in the State of Texas, although it often delegates OSSF permitting to local entities, such as county governments. In Bexar County, the entity tasked with OSSF permitting is the Bexar County Public Works Department (BCPWD). OSSF data were requested from the BCPWD within the first few months of the project and again in September 2019. Consequently, the OSSF data used in this study include all the OSSFs permitted as of September 19, 2019. A total of 1,412 OSSFs were permitted in the Helotes Creek watershed as of this date (**Figure 2-18)**.

2.5.5.2 TPDES and TLAP

TPDES and TLAP permit data were acquired from the TCEQ via open records requests and the online Central Registry Query (https://www15.tceq.texas.gov/crpub/index.cfm). Permit data were first collected for facilities in the contributing and recharge zones within Bexar County. However, due to limited permit records in the county, the search was expanded to include neighboring and nearby counties. Particular emphasis was placed on Hays and Travis counties, due to extensive research in that area regarding wastewater disposal practices (Herrington et al., 2010). These data were collected to inform hypothetical TPDES and TLAP solute-transport scenarios in the Helotes Creek watershed.

2.5.6 Bexar County Appraisal District data

Parcel and property data within the Helotes Creek watershed were collected from the Bexar County Appraisal District (BCAD). The data were used to demonstrate the growth and development that has occurred in the Helotes Creek watershed. Furthermore, the BCAD data allowed for an estimate of the number of OSSFs in the area, operating under the assumption that each property or household in the study area would be serviced by an OSSF. These data would also account for non-permitted OSSFs such as those installed prior to 1975 and those on properties with over 10 acres of land. **Figure 2-19** shows the property lines with properties colored according to the number of houses built on the land parcel.

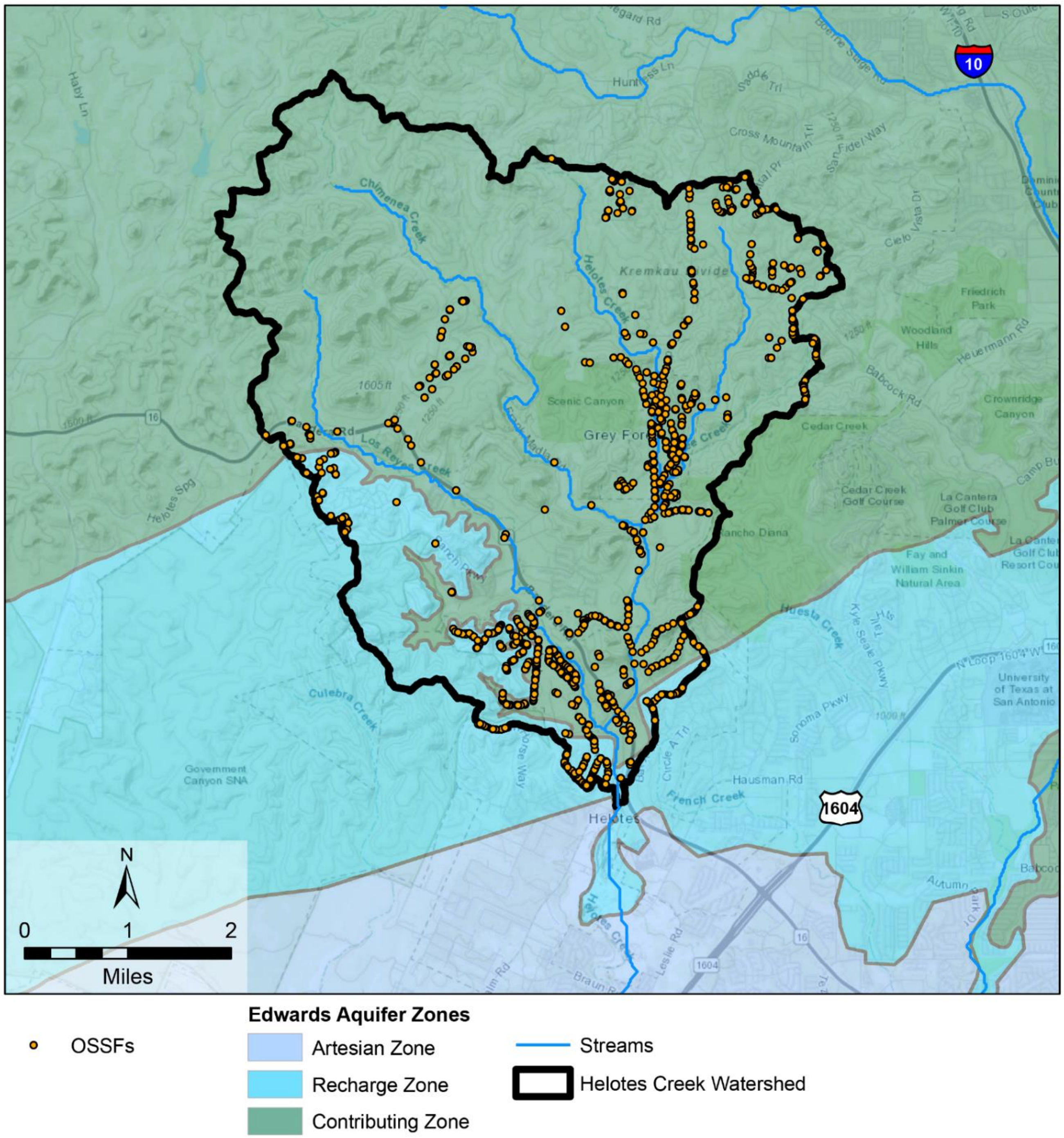


Figure 2-18 OSSFs that are permitted by the Bexar County Public Works Department in the Helotes Creek watershed.

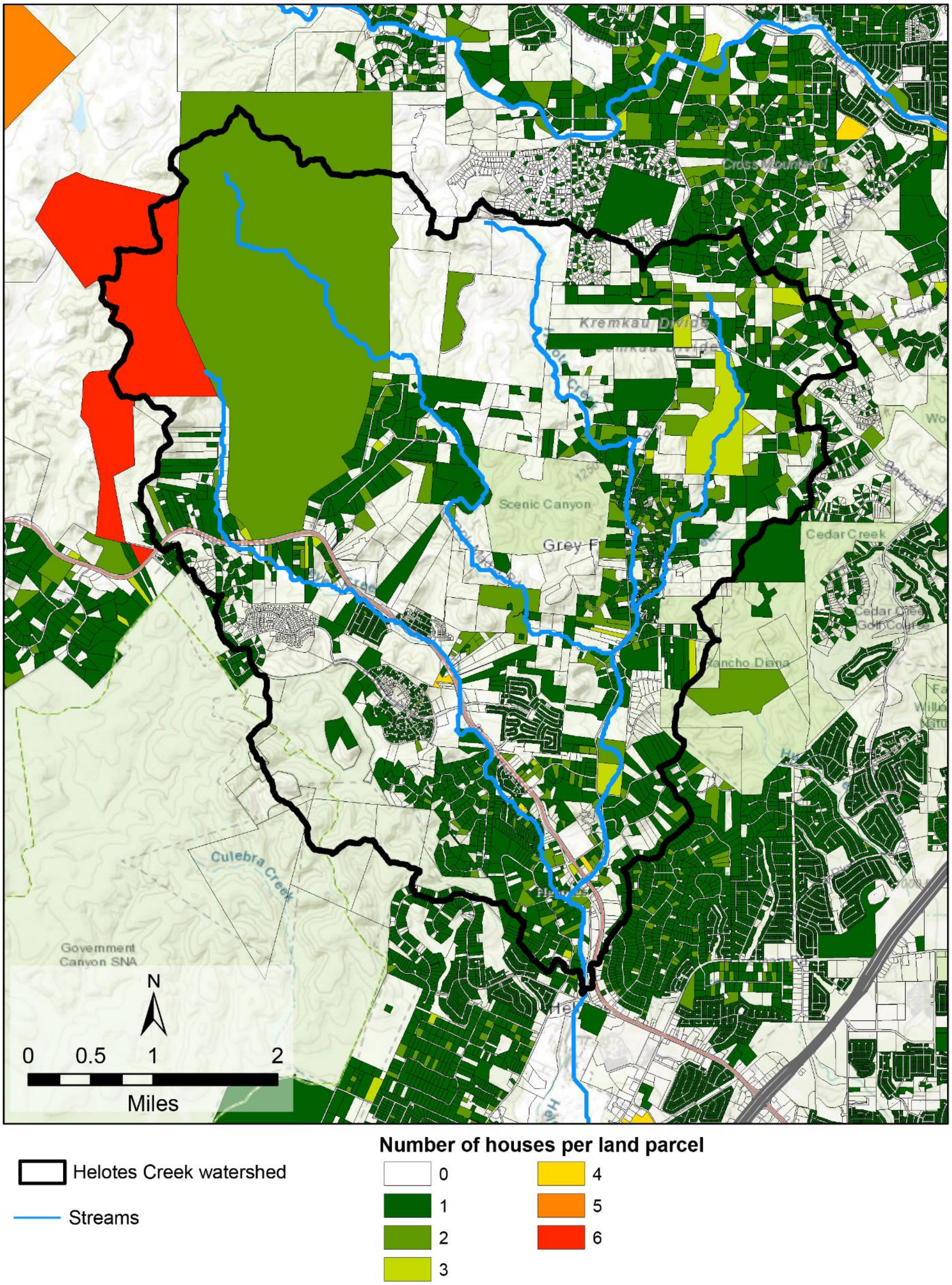


Figure 2-19 BCAD showing the number of houses built on each parcel of land in and around the watershed.

2.5.7 Water Chemistry Data

The Edwards Aquifer Authority and SwRI collaborated on two field sampling campaigns in the Helotes Creek watershed to assess water quality in the watershed and provide water-quality information for use with the Helotes Creek watershed Integrated Hydrologic Model. Sampling campaigns were undertaken in November-December 2018 (high-flow) and October 2019 (low-flow) with the goal of determining water-quality trends and the trophic state of the watershed and its sub-basins.

Surface-water samples were collected at ten sites in 2018 and five sites in 2019, the latter being the only sites out of the original ten where there was sufficient flowing water to sample (**Figure 2-20**). Temperature, pH and Dissolved Oxygen were measured in the field at the time of sample collection. Samples were sent out for laboratory analyses to test for major ions, isotopes, bacteria and nutrients and a suite of pharmaceuticals and personal care products. Results of each sample for bacteria and nutrients are detailed in **Table 2-3**.

Table 2-3 Results for bacteria and nutrient sampling and analysis at ten surface locations in the study area

Site	Date	P, Total	E. coli (MPN/100ml)	NO_3-N	TKN
HC 1	11/28/2018	ND	13	0.276	ND
HC 2	11/28/2018	ND	3	ND	0.201
HC 3	11/28/2018	ND	74	2.51	0.353
HC 4	11/28/2018	ND	12	1.12	0.333
HC 5	11/29/2018	ND	82	0.693	0.266
HC 6	11/29/2018	ND	4	1.76	0.282
HC 7	11/29/2018	ND	32	0.415	0.224
HC 8	11/29/2018	ND	26	0.214	0.299
HC 9	12/12/2018	ND	44	0.944	ND
HC 10	12/12/2018	ND	110	0.225	ND
HC 1	10/2/2019	ND	100	ND	0.222
HC 4	10/2/2019	0.026	150	ND	0.511
HC 5	10/2/2019	ND	60	ND	0.387
HC 6	10/3/2019	ND	84	2.41	0.254
HC 9	10/3/2019	0.021	410	ND	0.266

*ND = Not detected

Reporting Limits: P, Total = 0.02 mg/L; E. coli = 1 MPN/100 mL; NO_3-N = 0.05 mg/L; TKN = 0.2 mg/L

Groundwater samples were collected from six wells in 2019 (**Figure 2-21**). Temperature, pH and Dissolved Oxygen were measured in the field at the time of sample collection. Samples were sent out for laboratory analyses to test for major ions, isotopes, bacteria and nutrients and a suite of pharmaceuticals personal care products. Results for each sample for bacteria and nutrients are detailed in **Table 2-4**.

Table 2-4 Results for bacteria and nutrient sampling and analysis at six well locations in the study area.

Well	Date	P, Total	NH_3 - N	E. coli (MPN/100ml)	NO_3-N	TKN
AY-68-27-2WM	9/25/2019	0.058	ND	ND	0.783	0.38
AY-68-27-5LP	9/26/2019	ND	0.444	ND	ND	0.522
AY-68-19-5SK	10/15/2019	ND	0.101	ND	0.568	ND
AY-68-27-208	10/15/2019	ND	0.132	ND	ND	0.312
AY-68-27-2GH	10/16/2019	ND	ND	ND	ND	ND
AY-68-27-2HN	11/19/2019	0.022	0.319	50	ND	0.6

Reporting Limits: P, Total = 0.02 mg/L; NH_3 - N = 0.10 mg/L; E. coli = 1 MPN/100 mL; NO_3-N = 0.05 mg/L; TKN = 0.2 mg/L

Periphyton and seston samples were collected to provide additional insight into the trophic state of the Helotes Creek watershed. Periphyton and seston samples were collected at five of the surface-water sites in 2019 (**Figure 2-22**) and sent to the Center for Reservoir and Aquatic Systems Research (CRASR) for analyses. Periphyton samples were tested for chlorophyll-a (CHLA), ash-free dry mass (AFDM), phosphorus percentage, carbon and nitrogen percentage, and the stable isotopes $\delta^{13}C$ and $\delta^{15}N$. Seston samples were tested for CHLA and AFDM. Results from periphyton samples for carbon and nitrogen isotopes as well as %C and %N are shown in **Table 2-5**. Results from periphyton samples for chlorophyll-A are shown in **Table 2-6**. Results from seston samples for chlorophyll-A are shown in **Table 2-7**.

Table 2-5 Results from periphyton and seston sampling and analysis at five surface locations in the study area.

Site	Date	Periphyton $\delta^{13}C$ (‰)	Periphyton $\delta^{13}C$ (‰)*	Periphyton $\delta^{15}N$ (‰)	Periphyton $\delta^{15}N$ (‰)*	%C	%C*	%N	%N*
HC 1	10/2/2019	-17.87	-18.71	4.07	3.88	9.94	9.94	0.43	0.45
HC 4	10/2/2019	-19.79	-20.12	6.89	7.09	7.41	7.57	0.50	0.48
HC 5	10/2/2019	-17.57	-17.34	6.81	7.13	6.63	6.66	0.24	0.28
HC 6	10/3/2019	-19.33	-21.19	5.43	5.41	8.47	7.45	0.49	0.50
HC 9	10/3/2019	-21.93	-22.93	8.99	8.27	6.88	6.92	0.44	0.43

Table 2-6 Results from periphyton samples for chlorophyll-A (CHLA) at five surface locations in the study area.

Site	Date	Periphyton CHLA (mg/m^2)
HC 1	10/2/2019	19.59

HC 4	10/2/2019	17.90
HC 5	10/2/2019	27.49
HC 6	10/3/2019	47.11
HC 9	10/3/2019	43.09

Table 2-7 Results from seston samples for chlorophyll-A (CHLA) at five surface locations in the study area.

Site	Date	Seston CHLA (mg/sample)*
HC 1	10/2/2019	0.0739
HC 4	10/2/2019	0.0048
HC 5	10/2/2019	0.0040
HC 6	10/3/2019	0.0204
HC 9	10/3/2019	0.0233

Dodds et al. (1998) established a suggested classification of a stream or stream system's trophic state based on variables such as mean benthic chlorophyll, maximum benthic chlorophyll, sestonic chlorophyll, total nitrogen (TN), and total phosphorus (TP). Streams and stream systems with low concentrations of these constituents are classified as oligotrophic, moderate concentrations are classified as mesotrophic, and high concentrations as eutrophic. This classification scheme is detailed in **Table 2-8**.

Un-impacted Texas Hill County streams and rivers have low concentrations of these constituents and are classified as oligotrophic. Streams and rivers closer to urban areas that experience development have elevated concentrations these constituents in addition to bacteria, viruses, and emerging contaminants (Herrington, 2005; Herrington, 2008; Herrington & Scoggins, 2006, Mahler et al,. 2011 a,b,c; Musgrove et al., 2018). If concentrations are sufficiently high (**Table 2-8**), streams and rivers would be considered mesotrophic or even eutrophic. Streams with elevated concentrations of nutrients (i.e., phosphorous and nitrogen) are prone to algae growth and may exhibit undesirable qualities including reduced clarity, foul odor, and bad taste.

Table 2-8 Trophic classification of a stream (Dodds et al., 1998).

Variable	Oligotrophic-mesotrophic boundary	Mesotrophic-eutrophic boundary
Mean benthic chlorophyll (mg/m^2)	20	70
Maximum benthic chlorophyll (mg/m^2)	60	200
Sestonic chlorophyll (μg/L)	10	30

TN (μg/L)	700	1500
TP (μg/L)	25	75

Water-chemistry results were not useful when delineating the trophic state of Helotes Creek watershed, due to the fact that nitrogen and phosphorus sample concentrations were at or below the detection limits. For this reason, concentrations of nutrients in periphyton and sestonic samples, which have much lower detection limits compared with similar concentrations in water samples, were considered in order to determine the trophic state of Helotes Creek watershed.

Examination of the Helotes Creek seston data indicates that sestonic chlorophyll ranges from 4.04 to 73.9 μg/L (**Table 2-7**). The average sestonic chlorophyll value across the five sites is 25.3 μg/L. Sites HC1 and HC9 may overestimate this value due to the presence of some benthic material in the sample. If potentially overestimated values are excluded, the average sestonic chlorophyll value is 9.74 μg/L. These two averages would indicate that the Helotes Creek watershed was either in a slightly mesotrophic or oligotrophic state during the 2019 sampling period, respectively. There were no discernible sestonic trends for subwatersheds.

The periphyton (the source of benthic chlorophyll in this project) values for the Helotes Creek watershed range from 17.90 to 47.11 mg/m^2 with an average of 31.04 mg/m^2. This average value indicates that the Helotes Creek watershed is in an oligotrophic state, as it is below the oligotrophic-mesotrophic boundary for maximum benthic chlorophyll. However, the average value is also above the mean benthic chlorophyll value for the oligotrophic-mesotrophic boundary (20 mg/m^2), indicating the watershed could be slightly mesotrophic. There were no discernible periphyton trends for subwatersheds. Additional periphyton and seston sampling would be needed to further constrain the current trophic state of the Helotes Creek watershed.

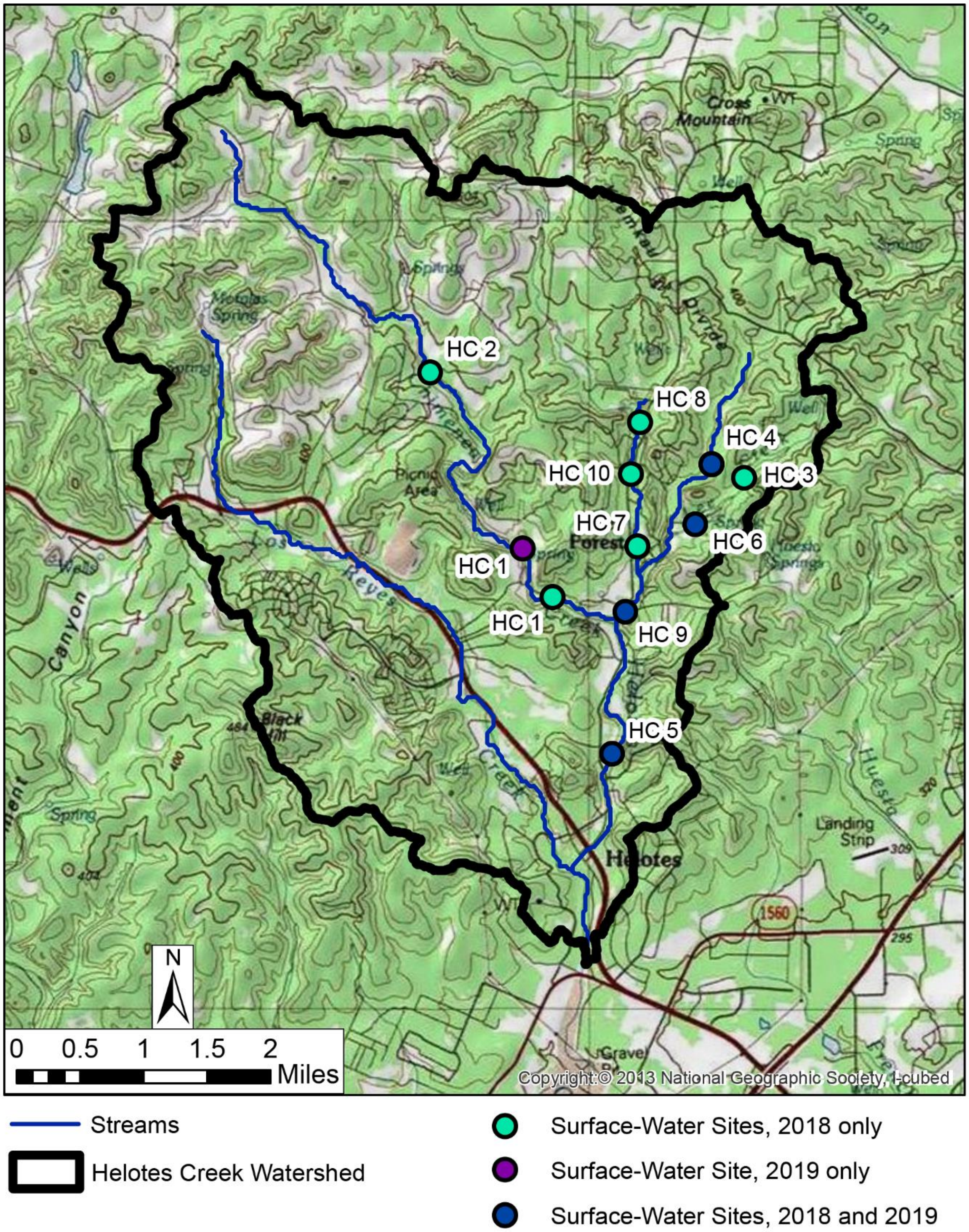


Figure 2-20 Surface water locations where water samples were collected in 2018 and 2019.

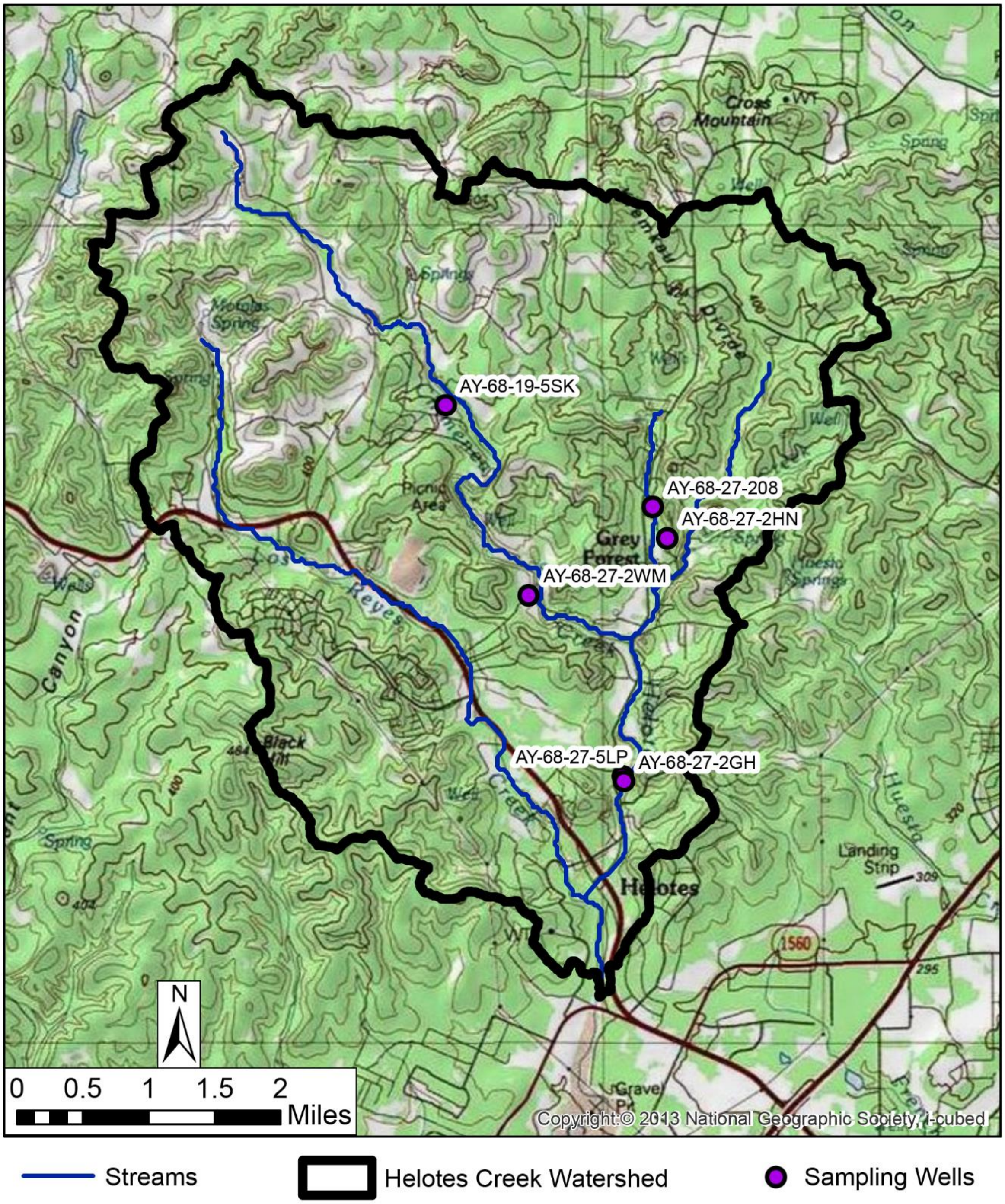


Figure 2-21 Well locations where water samples were collected in and 2019.

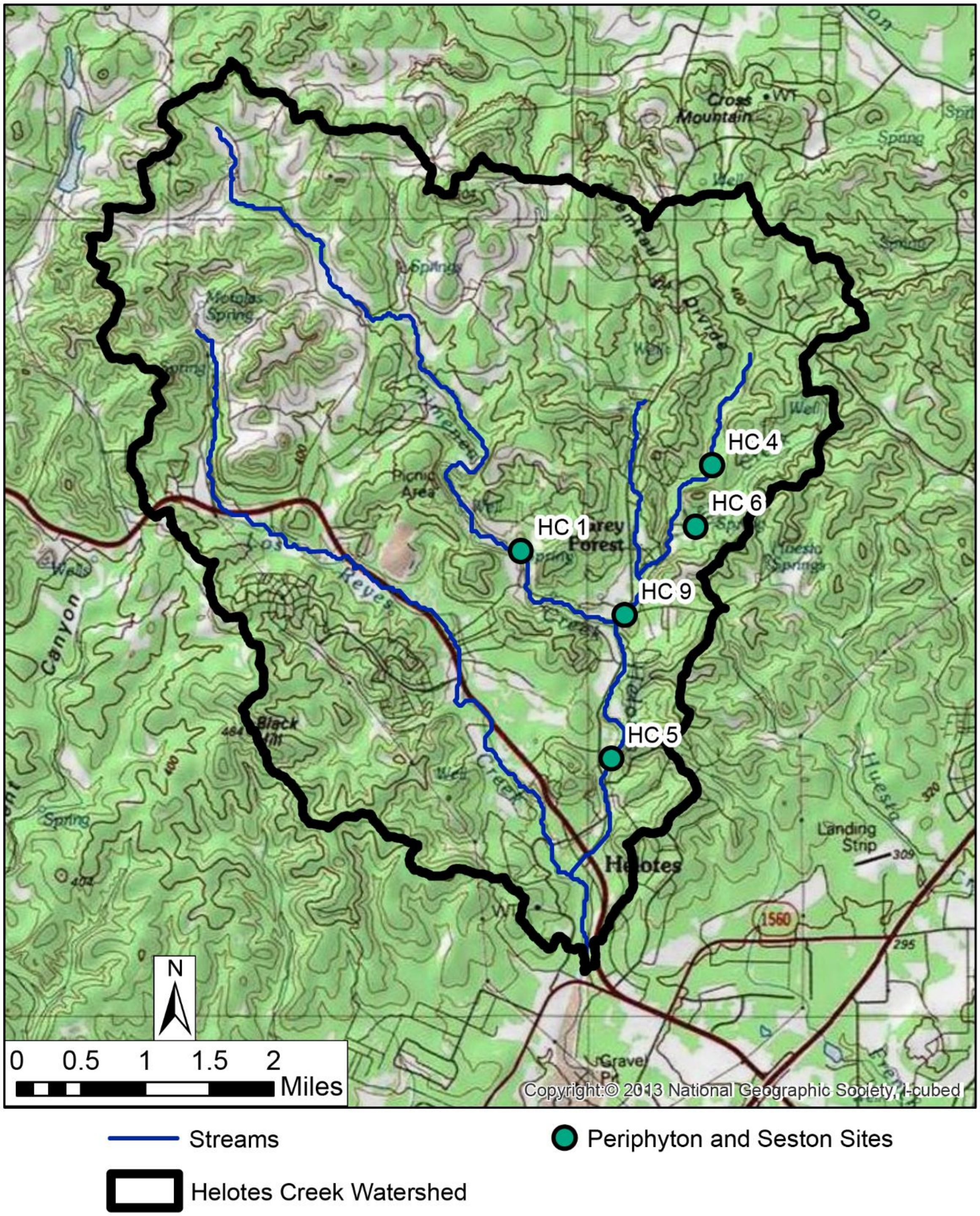


Figure 2-22 Surface water locations where water samples were collected for periphyton and seston 2019.

3 Wastewater Disposal Facility Scenarios

The scope of this project is to evaluate the impact of different wastewater disposal facilities on the quality of water that recharges the Edwards Aquifer. Because the Helotes Creek watershed study area does not include examples of all wastewater disposal facility types, hypothetical examples were identified to allow for assessment of the impact of each potential wastewater disposal facility type. Accordingly, eight hypothetical scenarios were identified to cover the reasonable range of wastewater disposal facility type. These scenarios assess the impact of future development in the watershed as well as that of current unpermitted facilities, current malfunctioning facilities, and possible alternative wastewater disposal facilities such as TPDES and TLAP facilities. Each scenario was evaluated using solute-transport simulation.

Limited data from and investigation of TPDES and TLAP facilities in Bexar County are available for scenario development. Studies in the Barton Springs segment of the Edwards Aquifer, in and around Austin, that document the rise in residential development since 2000 and a subsequent increase in impervious cover and an increase in treated wastewater disposal were used to augment scenario development. Given the similarities in urban growth between the two areas, patterns of development seen in the Barton Springs segment of the Edwards Aquifer are anticipated to occur in San Antonio and Bexar County. Investigations of the surge in the number of OSSF and TLAP facilities have been particularly useful (Herrington et al., 2010). These investigations document that the increase in treated wastewater disposal is linked to increased nitrates in surface water and groundwater and that this increase matches the timing of development (Mahler et al., 2011a; Musgrove, et al., 2016). Elevated nitrate concentrations detected downstream of TLAPs have been shown to be caused by inconsistent permitting practices (Ross, 2011).

Total nitrogen (TN) was selected as the conservative tracer for solute-transport simulations. Although nitrogen transforms throughout wastewater treatment processes (e.g., conversion of organic nitrogen to ammonium in septic systems), its quantity through these transformations doesn't significantly vary, thus making it a representative conservative tracer for the purposes of the transport simulation. Furthermore, nitrogen was selected due to its critical importance in assessing environmental health of natural water systems and because of its potential public health impacts. The solute-transport simulations consider both mass loading and relative nitrogen concentration before and after simulated wastewater disposal activities representative in each scenario. The receiving (impacted) body of the solute-transport simulation is that portion of the recharge zone of the Edwards Aquifer that is recharged by the Helotes Creek watershed plus that portion of the Edwards Aquifer that receives mass loading from the Helotes Creek watershed via transport through the Trinity Aquifer.

Two potential mechanisms could result in the Helotes Creek watershed impacting the quality of water recharged to the Edwards Aquifer south of the watershed:

1. **Interformational communication between the Trinity and Edwards aquifers:** In the study area, the Haby Crossing Fault in the southernmost portion of the watershed has resulted in the juxtaposition of the Cavernous Glen Rose (a Trinity unit) and the Kainer Formation (an Edwards unit) and other Edwards units. According to Ferrill et al. (2005), 60 – 100% of the faulted Trinity units in the area are in contact with Edwards units. In Johnson (2018), a study of the Helotes mulch fire of 2006 revealed potential hydraulic communication across the fault, indicated by the movement of contaminated water from the upper Glen Rose Formation into the Edwards Aquifer. A dye trace study conducted at Panther Springs Creek in another area of northern Bexar County also demonstrated direct hydraulic communication between the Trinity and Edwards aquifers in close proximity to the study area (i.e., within 5 miles) (Johnson, Schindel, & Veni, 2010). In the solute-transport simulations, the Cavernous Glen Rose was considered as the main transmissive Trinity unit in communication with Edwards units at the Haby Crossing Fault. As noted in Section 2.3.3, the conceptualization embraced in this evaluation is that Haby Crossing Fault does not act as a barrier to flow and that virtually all water that discharges from the Helotes Creek watershed north of Haby Crossing Fault eventually recharges the Edwards Aquifer in close proximity to the study area **(Figure 3-1)**.

2. **Additional recharge during storm events:** The lower portion of Helotes Creek slightly north and south of the USGS gage is within the Edwards Aquifer recharge zone or is located where the upper units of the Trinity Aquifer are exposed. These upper units have been shown to be in direct hydraulic communication with the Edwards Aquifer and effectively act as the Edwards Aquifer recharge zone (Gary et al., 2011). Immediately south of this part of the Helotes Creek watershed is a quarry where the Edwards Aquifer recharge zone has been exposed by removal of the Del Rio Clay. Observations following storm events have confirmed that water north of the quarry recharges the aquifer in this area.

3.1 OSSF Scenarios

The OSSFs were grouped into nine polygons for representation in the Helotes Creek watershed (**Figure 3-2**). These groupings were delineated primarily based on local fault blocks, although density and proximity of the OSSFs to one another were also considered. OSSFs that were geographic outliers (e.g., relatively isolated from areas of high OSSF density) were added to the totals for the nearest OSSF group polygon. **Table 3-1** lists the estimated number of OSSFs per group polygon. **Table 3-2** shows the details of each scenario for quick reference.

Table 3-1 Estimated number of OSSFs per group polygon.

Group Number	Number of OSSFs
1	176
2	334
3	105
4	103
5	352
6	87
7	101
8	89
9	65
Total:	**1,412**

3.1.1 Base Case

The Base Case rtepresents the current number of permitted on-site sewage facilities in the Helotes Creek watershed. Data received from the Bexar County Public Works Department in September 2019 identifies 1,412 permitted OSSFs in the watershed. The Base Case depicts the current state of the Helotes Creek watershed, given that OSSFs are the only type of wastewater disposal practice active in the watershed.

Mass loading from the OSSFs is to the surface of the water table. Total nitrogen mass loading for the Base Case is 40 mg/L, a value selected based on studies that examined nitrogen contributions of septic systems to water resources (Barrett & Charbeneau, 1997; Canter & Knox, 1985). The average flow from these septic systems is estimated at 680 L/capita/day (Barrett & Charbeneau, 1997; U.S. EPA, 1980).

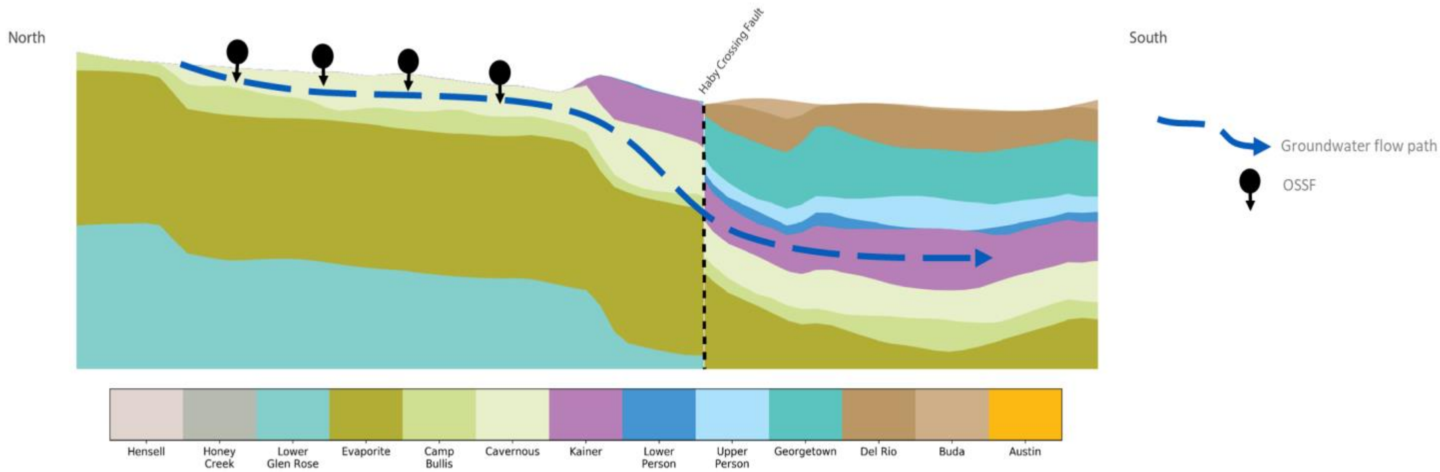


Figure 3-1 Cross-section at Haby Crossing Fault showcasing theoretical flow path into the Edwards Aquifer.

3.1.2 Scenario 1 – Permitted and Hypothetical Non-Permitted OSSFs

Scenario 1 simulates the impact of both permitted OSSFs and potential non-permitted OSSFs. In Bexar County, OSSFs installed prior to 1975 were required to be registered, although many may not have been officially accounted for in the Bexar County database. Furthermore, Bexar County differs from most Texas counties in that OSSFs must be permitted regardless of the property size. Therefore, even OSSFs serving properties of 10 acres or larger should be included in the database. The only potential OSSFs that may not yet be registered would be any that were not grandfathered after 1975. In order to account for potential discrepancies between the number of permitted OSSFs (Base Case) and the actual total number of OSSFs (permitted + non-permitted), 2018 data from the Bexar County Appraisal District (BCAD) were acquired (**Figure 3-3**). The assumption made is that each property in the BCAD records is served by at least one OSSF, regardless of the property's age or acreage. In order to estimate non-permitted OSSFs that date to prior to 1975, BCAD data were used to determine the number of households built prior to 1975. These properties were then compared with the OSSF shapefile obtained from the Bexar County Public Works Department to find the number of households that may be equipped with or were at some point equipped with OSSFs but are not registered.

This method prevented duplication of OSSFs for properties that were established during or after 1975 and whose OSSFs are most likely included as permitted OSSFs in the Bexar County Public Works Department records. The non-permitted OSSFs were grouped into the same polygons as those developed for the Base Case. The combined number of permitted OSSFs (1,412) and non-permitted proxy OSSFs (216) is 1,627 OSSFs.

Similar to the Base Case, mass loading is to the surface of the water table. The total nitrogen mass loading for Scenario 1 is 40 mg/L. The average flow from these septic systems is maintained at 680 L/capita/day.

3.1.3 Scenario 2 – Failing OSSFs

Scenario 2 simulates the impact of OSSFs under hypothetical conditions in which a portion of the OSSFs are failing. For this scenario, a "failing" septic system would result in higher mass loading of total nitrogen. According to a study by Reed, Stowe, and Yanke, LLC (2002) that focused on the magnitude of chronically malfunctioning OSSFs in Texas, about 13% of the Texas permitted OSSFs are likely failing. They found that the systems most likely to be chronically malfunctioning were old septic systems constructed prior to the establishment of regulations. These systems were typically grandfathered into their respective regulatory databases without insuring performance compliance. Therefore, for Scenario 2, 13% of OSSFs per grouping are considered as potentially malfunctioning (**Figure 3-4**).

Mass loading is to surface of the water table, however, total nitrogen mass loading for the 13% of malfunctioning OSSFs in Scenario 3 is 80 mg/L, a value double of that assigned to a properly functioning OSSF. The average flow from these septic systems is maintained at 680 L/capita/day, the average flow of OSSFs found in the literature (Barrett & Charbeneau, 1997; U.S. EPA, 1980).

3.1.4 Scenario 3 – Future increase in OSSFs

Scenario 3 simulates the impact of OSSFs based on the potential increased number of OSSFs that would be present in five years. The projected number of OSSFs is based on the projected population growth in Bexar County and Helotes, as well as the projected growth in the number of households in both. Although much of the study area is outside of the city limits of Helotes and in either the City of Grey Forest or in the Extra Territorial Jurisdiction of the cities of Helotes, Grey Forest, or San Antonio, growth projections for the City of Helotes are used to establish estimated increases in population and households for the purposes of this study.

According to the U.S. Census Bureau, Bexar County and the City of Helotes experienced an increased change in population of 15.8% and 30.2%, respectively, between 2010 and 2018. In comparison, a growth-rate profile prepared by the Helotes

Economic Development Corporation in 2014 projected an increase in population of 17.5% between 2014 and 2019 and a projected growth rate of 29.7% between 2010 and 2019. With respect to the number of households, the same profile projected a growth of 6.4% between 2010 and 2014 and a growth rate of 15.7% between 2014 and 2019.

Scenario 3 assumes that an OSSF will be installed at each new household in the northern portion of the watershed over the next 5 years. No additional households are added to the southern portion of the watershed because this area is essentially built out and no additional residential construction is anticipated. Consequently, Scenario 3 assumes a growth in the number of OSSFs of 15% relative to the number permitted OSSFs in the northern portion of the watershed as of September 2019. This would result in a total of 1,516 OSSFs by September 2024 (**Figure 3-5**). Most of the new OSSFs in Scenario 3 are added to the OSSF groupings in the northern reaches of the watershed, since this is where there is the greatest potential for development of new subdivisions. Mass loading is to the surface of the water table. The total nitrogen for Scenario 3 is 40 mg/L and average flow from these septic systems is maintained at 680 L/capita/day.

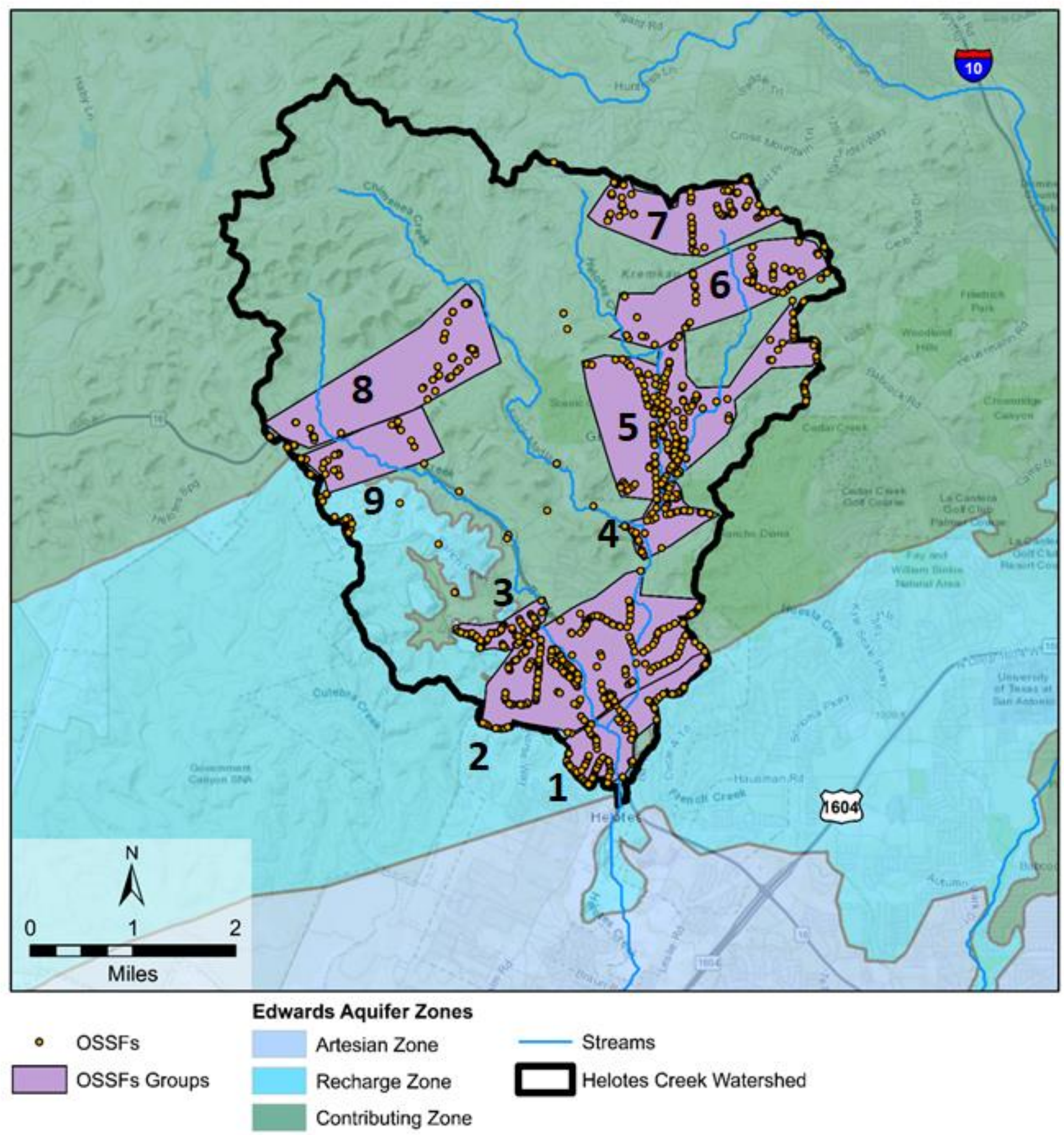


Figure 3-2 Permitted OSSFs (orange points) and groupings (purple polygons) in the Helotes Creek watershed, OSSF group numbers included (Base Case).

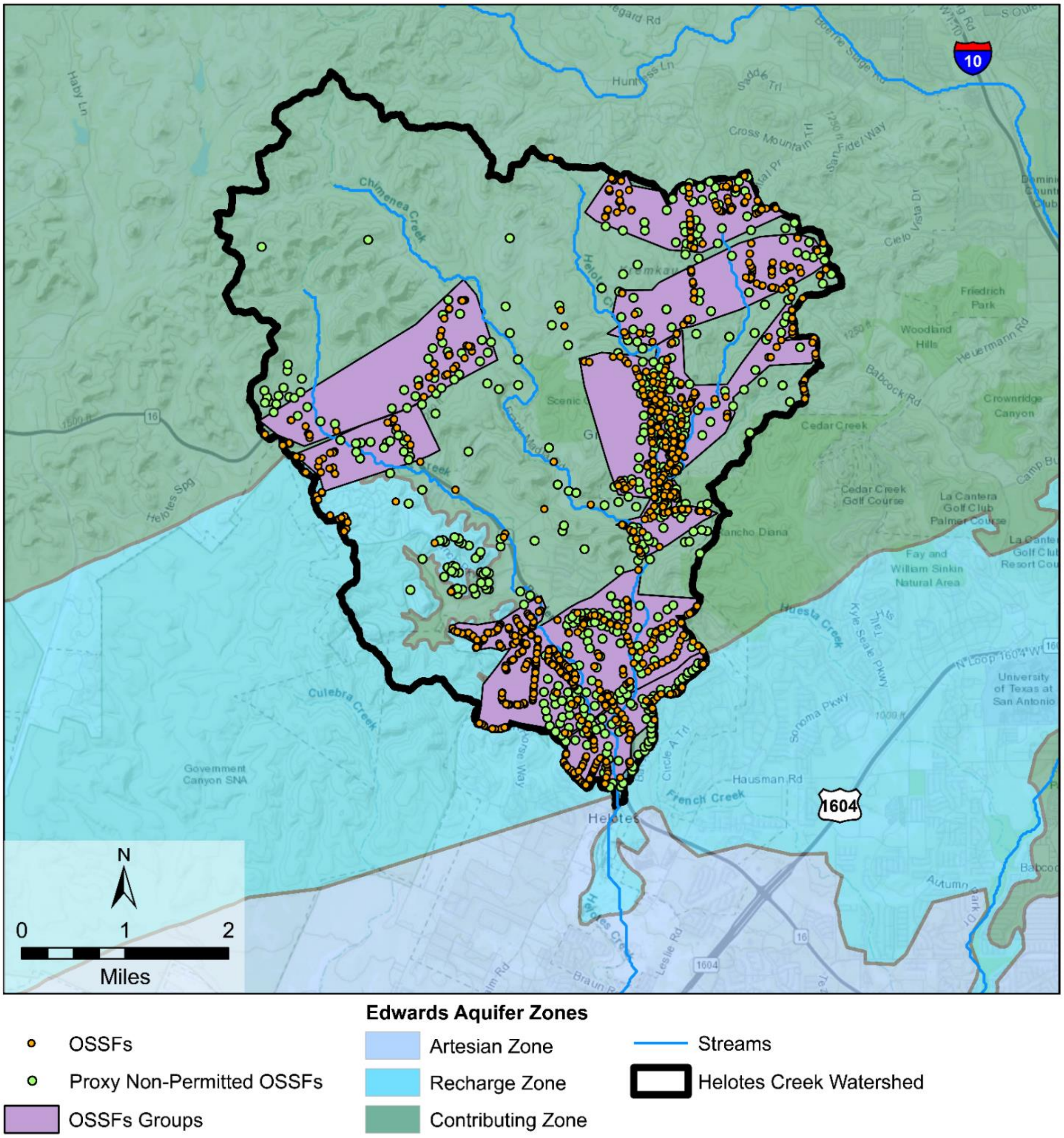


Figure 3-3 Map of permitted and proxy non-permitted OSSFs (Scenario 1).

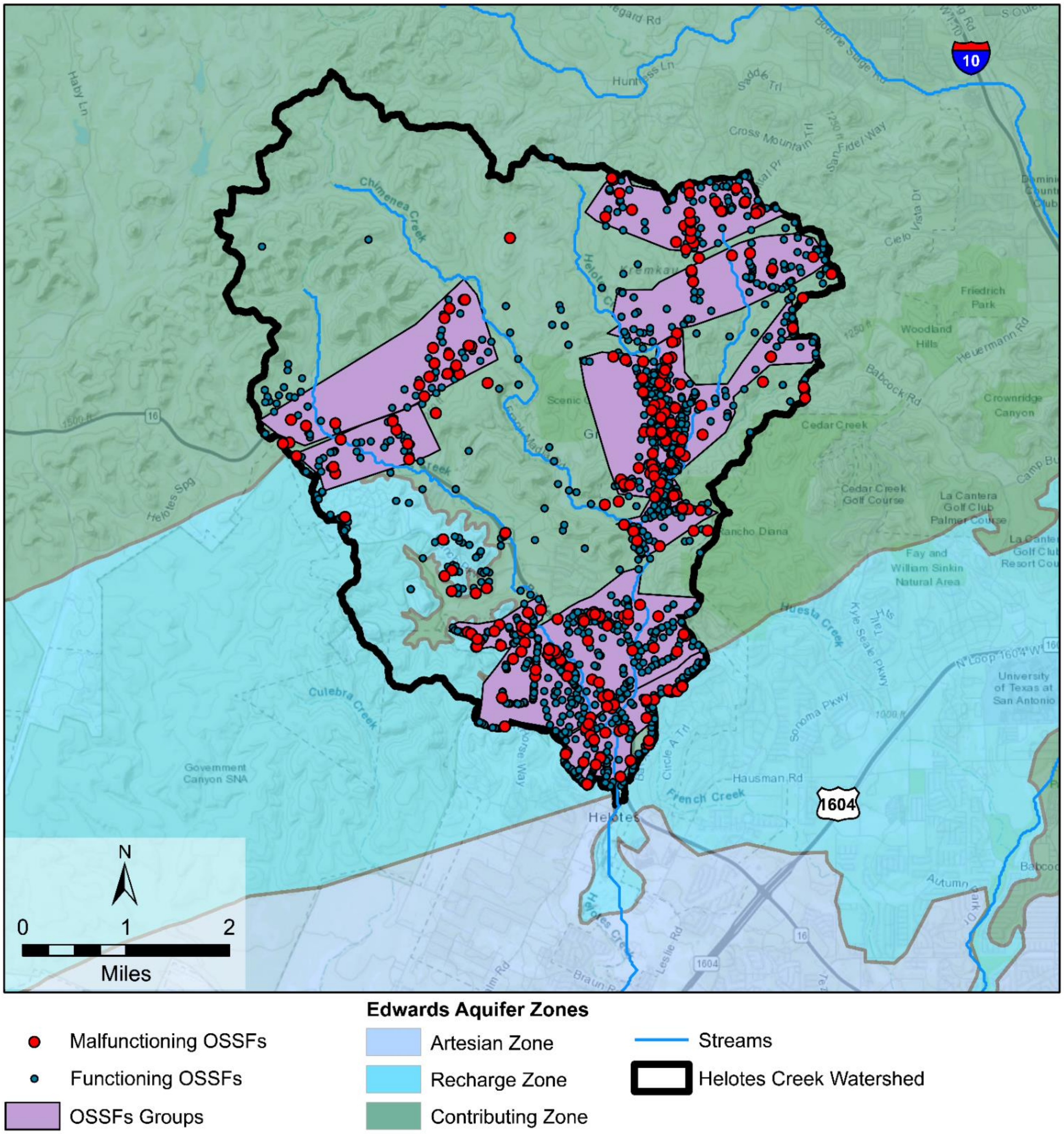


Figure 3-4 Depiction of operational and malfunctioning OSSFs in the Helotes Creek watershed (Scenario 2).

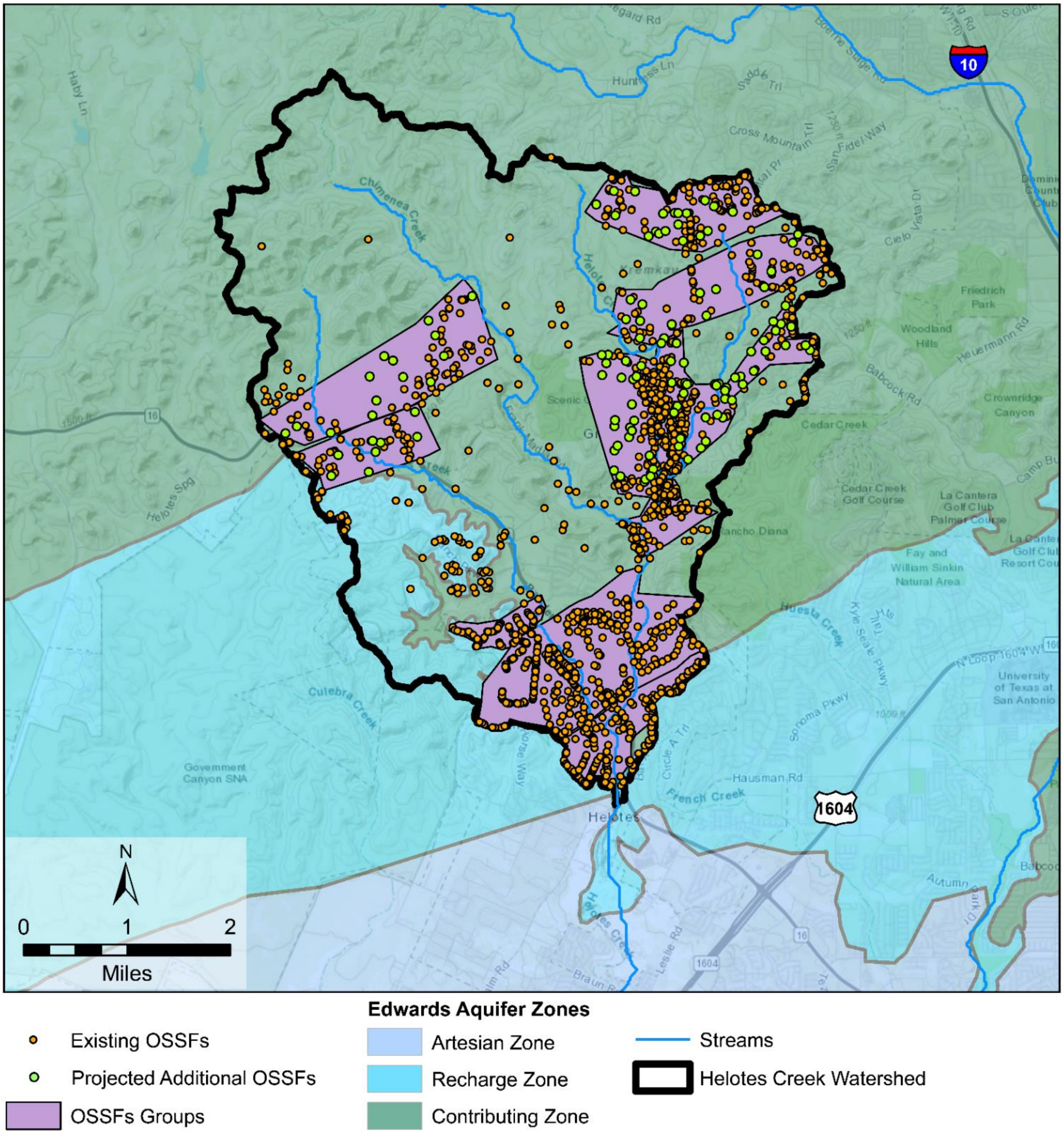


Figure 3-5 Depiction of existing OSSFs and projected example locations for new OSSFs in 5 years (Scenario 3).

3.2 TLAP Scenarios

3.2.1 Scenario 4 – Northern TLAP SADDS

Scenario 4 simulates the impacts of a hypothetical TLAP Subsurface Area Drip Dispersal System (SADDS) in a northern portion of the Helotes Creek watershed **(Figure 3-6)**, particularly within the less developed Chimenea Creek subwatershed. In this scenario, effluent is injected no deeper than 4 feet into the subsurface (per regulatory standards) over 32 acres of land (30 TAC §222). Furthermore, the TLAP in this location would hypothetically replace the OSSFs in OSSF groups 8 and 9, while the other OSSF groups in the eastern and southern portions of the watershed would remain active.

Mass loading is to the surface of the water table. The application rate is 0.1 gal/ft^2/day, which comports with the maximum permitted application rate in this region of Texas (30 TAC §222). The maximum flow for the facility at this application rate is 0.14 million gallons per day (MGD). The concentration of total nitrogen in effluent from a given wastewater disposal plant varies based on the process designs of the plant (U.S. EPA, 1980). These values can range from 5 mg/L to over 35 mg/L. For Scenario 4, the selected total nitrogen mass loading is set at 20 mg/L, within the range of expected total nitrogen mass loadings of packaged wastewater disposal facility.

3.2.2 Scenario 5 – Southern TLAP SADDS

Scenario 5 simulates the impacts of a hypothetical TLAP Subsurface Area Drip Dispersal System (SADDS) in a southern portion of the Helotes Creek watershed (**Figure 3-7**), particularly within the more developed Lower Helotes Creek subwatershed. This location is closer to where either two of the recharge processes into the Edwards Aquifer would occur. In this scenario, effluent is injected no deeper than 4 feet into the subsurface (per regulatory standards) over 13 acres of land. Furthermore, the TLAP in this location would hypothetically replace the OSSFs in OSSF group 2, while the other OSSF groups in the watershed would remain active.

Mass loading is to the surface of the water table. The application rate is 0.1 gal/ft^2/day, which comports with the maximum permitted application rate in this region of Texas (30 TAC §222). The maximum flow for the facility at this application rate is 0.05 million gallons per day. The concentration of total nitrogen in effluent from a given wastewater disposal facility varies based on the process designs of the plant (U.S. EPA, 1980). These values can range from 5 mg/L to well over 35 mg/L. For Scenario 5, the selected total nitrogen concentration is 20 mg/L which is within the range of expected total nitrogen concentrations in effluent from packaged wastewater disposal facility.

3.2.3 Scenario 6 – Northern TLAP SS

Scenario 6 simulates the impacts of a hypothetical TLAP Surface Spray/Irrigation (SS) facility in a northern portion of the Helotes Creek watershed (**Figure 3-6**), such as the less developed Chimenea Creek subwatershed. In this scenario, effluent is applied over a 32-acre land surface (e.g., irrigation field). Furthermore, the TLAP at this location would hypothetically replace the OSSFs in OSSF groups 8 and 9, while the other OSSF groups in the eastern and southern portions of the watershed would remain active.

Mass loading is split between runoff and the water table. The application rate is 0.060 gal/ft^2/day, which is within the range of application rates of similar facilities in other areas of the Texas Hill Country (30 TAC §309). The maximum flow for the facility at this application rate is 0.86 million gallons per day. The concentration of total nitrogen in effluent from a given wastewater disposal facility varies based on the process designs of the plant (U.S. EPA, 1980). These values can range from 5 mg/L to well over 35 mg/L. For Scenario 6, the selected total nitrogen mass loading concentration is 20 mg/L, which is within the range of expected total nitrogen concentrations in effluent from packaged wastewater disposal facilities.

3.2.4 Scenario 7 – Southern TLAP SS

Scenario 7 simulates the impacts of a hypothetical TLAP Surface Spray/Irrigation facility in a southern portion of the Helotes Creek watershed (**Figure 3-7**), notably within the more developed Lower Helotes Creek subwatershed. In this scenario, effluent is applied over a 13-acre land surface (e.g., irrigation field). Furthermore, the TLAP at this location would hypothetically replace the OSSFs in OSSF group 2, while the other OSSF groups in the watershed would remain active.

Mass loading is split between runoff and the water table. The application rate is 0.060 gal/ft^2/day, which is within the range of application rates of similar facilities in other areas of the Texas Hill Country (30 TAC §309). Maximum flow for the facility is 0.34 million gallons per day. The concentration of total nitrogen in effluent from a given wastewater disposal facility varies based on the process designs of the plant (**Figure 3-7**). These values can range from 5 mg/L to well over 35 mg/L. For Scenario 7, the selected total nitrogen concentration is 20 mg/L, within the range of expected total nitrogen concentrations in effluent from packaged wastewater disposal facilities.

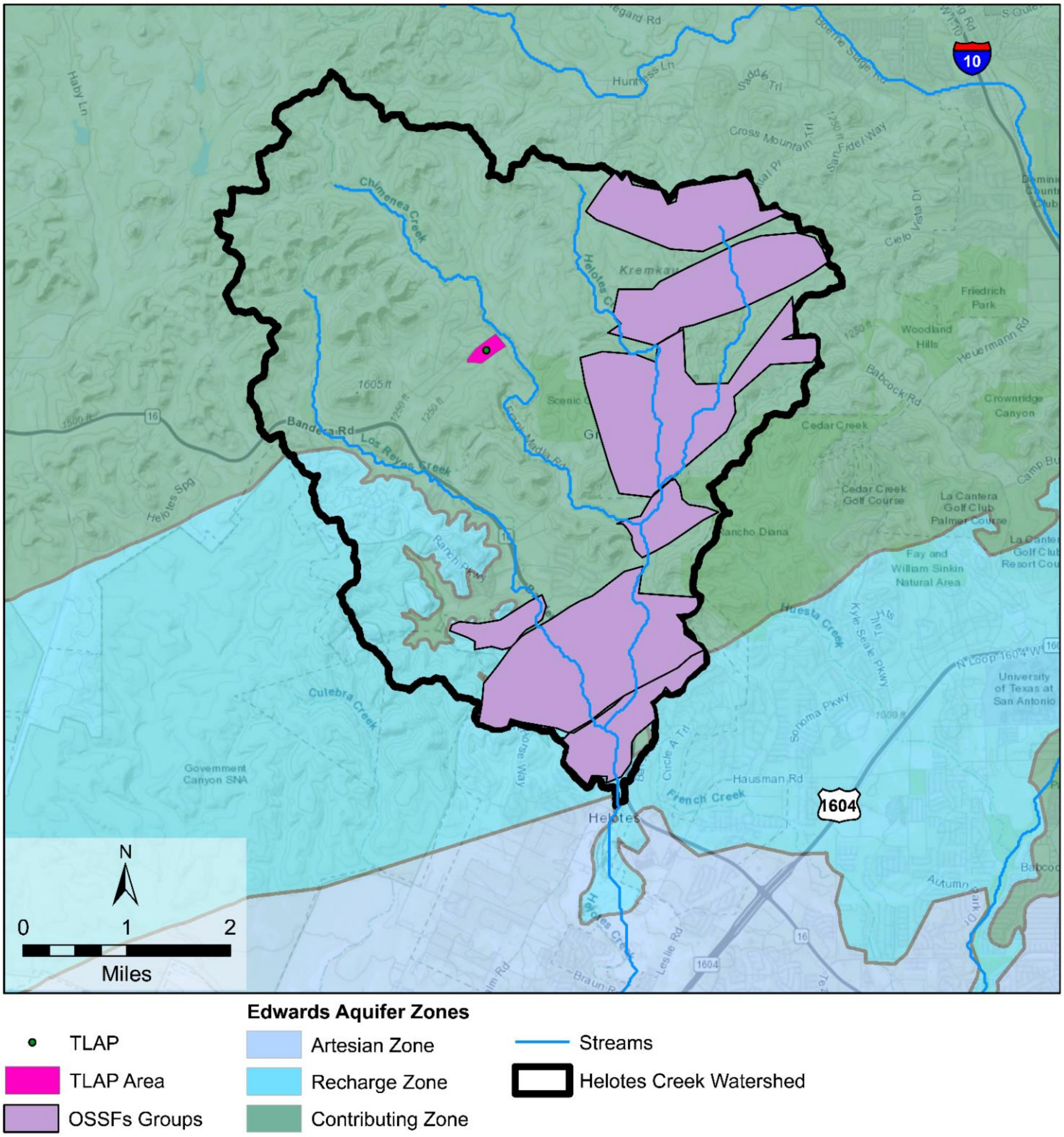


Figure 3-6 Map depicting location of northern TLAP facility location for Scenarios 4 and 6.

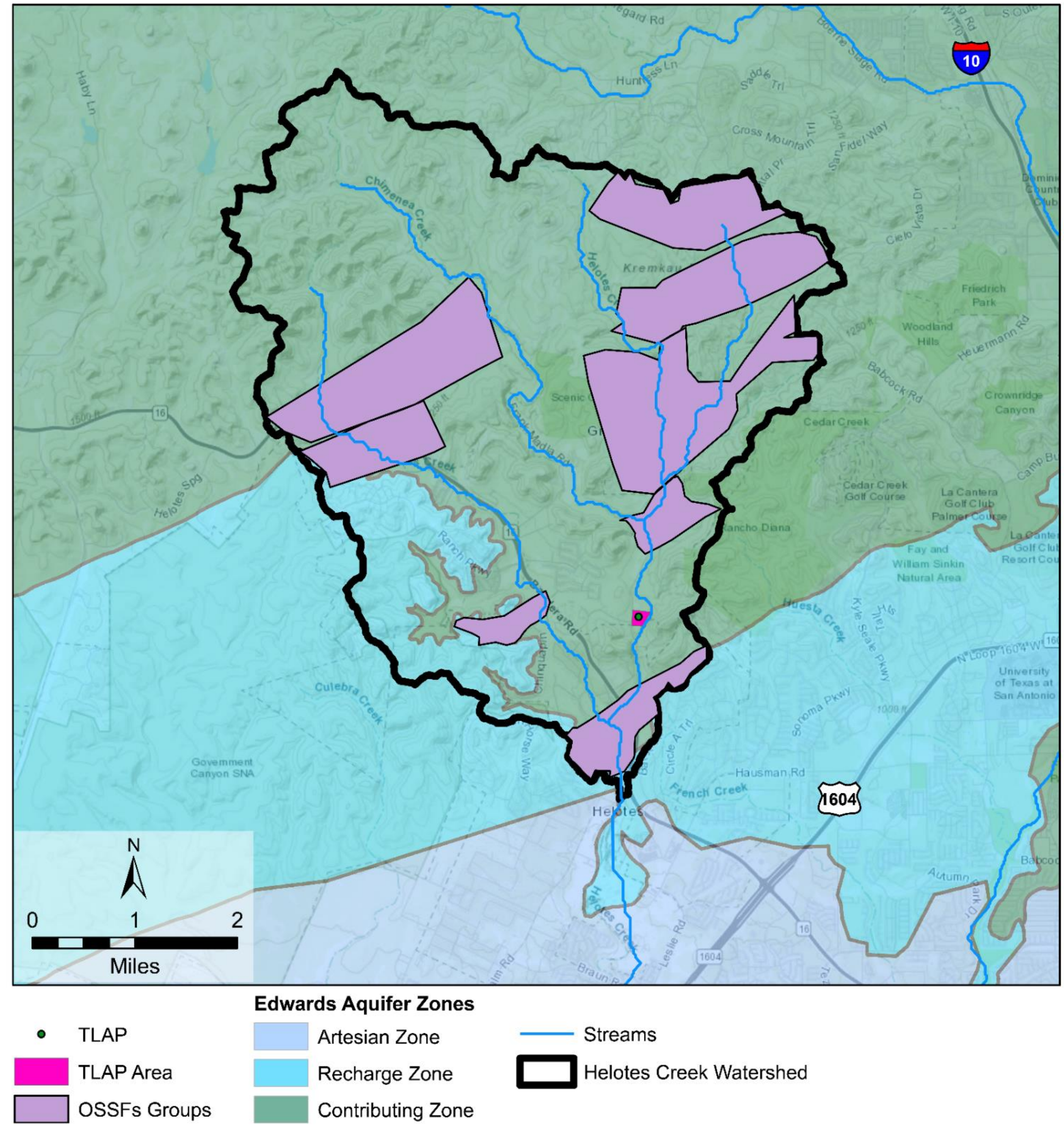


Figure 3-7 Location of TLAP facility for Scenarios 5 and 7.

3.3 TPDES Scenarios

3.3.1 Scenario 8

Scenario 8 simulates the impacts of a hypothetical TPDES in a southern portion of the Helotes Creek watershed (**Figure 3-8**), particularly within the more developed Lower

Helotes Creek subwatershed. In this scenario, effluent is released into the nearest segment of Helotes Creek where stream flow is perennial.

Scenario 8 assumes that all households within OSSF group 2 would be connected to the TPDES for wastewater treatment and disposal. The assumed wastewater flow is 0.80 million gallons per day, based on the permitted flows of similar TPDES facilities in the region, such as the Bridgewood Wastewater Treatment Plant located in the Leon Creek subwatershed which is adjacent to the Helotes Creek watershed.

All mass loading is applied to runoff. The concentration of total nitrogen in effluent from a given wastewater disposal facility varies based on the process designs of the plant (U.S. EPA, 1980). These values can range from 5 mg/L to well over 35 mg/L. For Scenario 8, the selected total nitrogen concentration is 20 mg/L, within the range of expected total nitrogen concentrations of effluent from packaged wastewater disposal facilities.

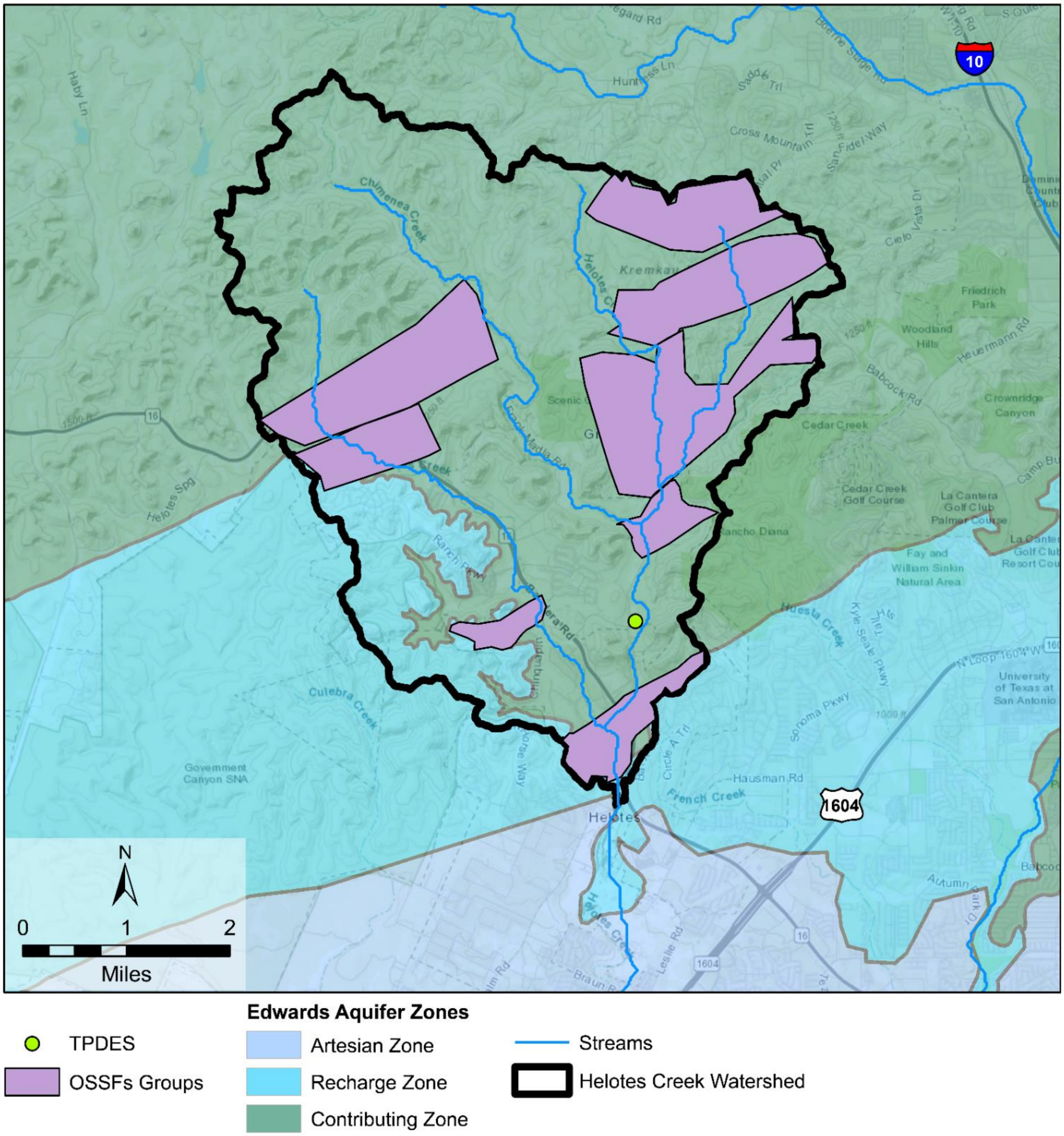


Figure 3-8 Location of hypothetical TPDES facility (Scenario 8).

Table 3-2 Wastewater facility scenarios according to wastewater disposal method.

Treatment Method		Scenario	Summary	Mass Loading	Total Nitrogen Concentration	Total OSSFs	OSSFs (MGD)	TLAP/ TPDES (MGD)	Total Flow (MGD)
OSSF		BC	Permitted OSSFs	Water table	40 mg/L	1412	0.25	-	0.25
		1	Permitted and proxy Non-Permitted OSSFs	Water table	40 mg/L	1627	0.29	-	0.29
		2	13% Malfunctioning OSSFs	Water table	40 mg/L (1,685 functioning OSSFs) 80 mg/L (252 malfunctioning OSSFs)	1412	0.25	-	0.25
		3	Year 2024 Projected Growth	Water table	40 mg/L	1516	0.27	-	0.27
TLAP	SADDS	4	Northern part of watershed	Water table	20 mg/L	1255	0.23	0.14	0.37
		5	Southern part of watershed	Water table	20 mg/L	1080	0.19	0.05	0.24
	Surface Spray/Irrigation	6	Northern part of watershed	Runoff and water table	20 mg/L	1255	0.23	0.86	1.09
		7	Southern part of watershed	Runoff and water table	20 mg/L	1080	0.19	0.34	0.53
TPDES		8	Southern part of watershed	Runoff	20 mg/L	1080	0.19	0.80	0.99

4 Implementation

While there has been considerable effort to model groundwater flow in the Edwards Aquifer and associated aquifers, an integrated surface-water/groundwater model and an associated solute-transport model within the San Antonio segment of the Edwards Aquifer is lacking. Here we present an integrated hydrologic transport representation that provides the means to simulate solute transport and evaluate the scenarios needed for wastewater disposal facility evaluation. A hydrogeological framework model based on previous work by Ferrill et al. (2005) and Clark et al. (2016) served as the basis for the integrated hydrologic transport representation. The project team developed an integrated surface-water/groundwater model using GSFLOW software (https://water.usgs.gov/water-resources/software/gsflow/GSFLOW_Release_Notes_2.1.0.pdf) that links the watershed model PRMS-IV (https://water.usgs.gov/water-resources/software/PRMS/ release_notes_prms_5.0.0.pdf) and the groundwater model MODFLOW 2005 (https://water.usgs.gov/water-resources/software/MODFLOW-2005/release.txt). Results from integrated hydrologic modeling were used in tandem with MODPATH 7 software (https://water.usgs.gov/water-resources/software/MODPATH/release.txt) and ZONEBUDGET software (Harbaugh, 1990) to determine flow pathways and volumetric flow rates for input to a transport model developed with GoldSim 12.1 (https://www.goldsim.com/). This model assembly provides a valuable tool to target which wastewater disposal facility types and locations pose the greatest risks to degradation of recharge to the Edwards Aquifer.

4.1 Framework Model Implementation

This study relied on refined geologic and hydrostratigraphic studies of the Edwards and Trinity aquifers in Bexar County (Clark et al., 2016) during framework model development. The methodology employed to develop the geologic framework model using the Petrel software package (https://www.software.slb.com/products/petrel) is described in Appendix B. Average thicknesses of model layers, surface topography, and well control were incorporated into the Petrel model. The geologic framework model in Petrel provided the basis for hydrologic framework development and stratigraphic data implementation. The construction of the geological framework model provided two-dimensional surfaces of top elevations of hydrostratigraphic units. A total of 41 normal faults mapped in the area were included in the geologic framework model. The faults were assumed to cut each horizon in the model domain, with fault offsets estimated based on the mapping of Clark et al. (2016).

Point representations of stratigraphic picks exported from the Petrel geologic framework model were used to develop the hydrologic framework model. Specifically, Triangular Irregular Networks (TINs) of formation top elevations in the model domain were created to provide 3-D volumes that could be directly mapped onto the MODFLOW grid.

The ground surface of the hydrologic framework model was constrained using the digital elevation model (DEM) (Section 2.5.3). Surfaces of formation-top elevations were created for the Hensell, Honey Creek, Lower Glen Rose, Evaporite/Fossiliferous, Camp Bullis, Cavernous, Kainer, Lower Person, Upper Person, Georgetown, Del Rio, Buda, and Austin/Eagle Ford hydrostratigraphic units using stratigraphic pick interpretations (see Appendix B). Thirteen stratigraphic layers are represented in the model domain and honor the refined hydrostratigraphic interpretations in the study area made by Clark et al. (2016)

A solids model was pre-assembled in Esri ArcGIS 10.5 (https://www.esri.com/en-us/arcgis/about-arcgis/overview) using the hydrostratigraphic layers to provide visualization of conceptual model development and confirmation and visualization of model results. The solids model was created by extruding volumes between adjacent TIN surfaces to create a volumetric representation of the formation thicknesses. The TIN extrusions were laterally bounded by the polygons created from faults in the geologic framework model and exported to the hydrostratigraphic framework model. The resulting hydrologic framework model preserved fault vertical offset (throw) between layers, but simplified the dip of faults to be vertical. This simplification was necessary because the resolution of the groundwater model grid was too coarse to capture non-vertical dips. Moreover, this simplification was thought to be reasonable because it captures first order thinning of aquifer and aquitard units, juxtaposition relationships across faults, and displacement of stratigraphic units.

4.2 Integrated Hydrologic Modeling

The freely available, open source GSFLOW 2.0.0 integrated hydrologic modeling software was selected to model runoff, unsaturated zone flow, and saturated zone flow in the Helotes Creek watershed. Hydrologic modeling was necessary to quantitatively constrain the range of rates of transport from potential wastewater disposal sources in the Helotes Creek watershed to the Edwards Aquifer that might occur. Because potential transport pathways comprise interacting streams and groundwater, integrated hydrologic modeling software was necessary to consistently account for both stream characteristics and regional groundwater flow patterns. The ability to represent coupled surface runoff and regional groundwater flow with the watershed model was critical to the effort to accurately simulate the hypothesized transport pathways to the Edwards Aquifer and account for feedbacks between surface water and groundwater. The integrated hydrologic model implemented in GSFLOW is conceptually intermediate between the extremes of (i) simulating surface-water and groundwater balances with separate codes and (ii) simultaneously solving the independently complete set of surface-water and groundwater equations with a fully-coupled code. GSFLOW uses two specialized and independent codes, PRMS-IV and MODFLOW, to address different parts of the overall water balance. PRMS 5.0.0 solves the water balance for runoff and water in the shallow soil zone, while MODFLOW 1.12.0 solves the water balance for flows in streams and lakes, the deeper unsaturated zone, and the saturated zone. GSFLOW ensures that PRMS and MODFLOW represent a fully-coupled and internally consistent hydrologic system by passing a consistent amount of water across the domain interface separating the two codes at every time step.

Model parameterization and calibration were separated into three steps. First, a standalone PRMS model was developed and parameterized for Helotes Creek watershed and calibrated independently using PEST 17.05 software (http://www.pesthomepage.org/Downloads.php#hdr1). Then, a MODFLOW model was developed and input files for both MODFLOW and PRMS were grouped in a directory structure suitable for GSFLOW. Additional PRMS input files for parameters pertaining to soil-zone characteristics and mapping between HRU's and MODFLOW finite-difference cells were created. GSFLOW-specific PRMS parameters were manually calibrated to ensure reasonable runoff and recharge rates. Finally, MODFLOW parameters were calibrated using PEST software and running the full GSFLOW model with PRMS and MODFLOW active.

4.2.1 PRMS-IV Model Implementation

Precipitation-Runoff Modeling Software (PRMS) IV is a surface-water model that is capable of simulating hydrologic response such as streamflow, evapotranspiration, and groundwater recharge in a watershed. A full description of the model including inputs and results can be found in the PRMS-IV Appendix.

The watershed was divided into 23 hydrologic response units (HRUs), as the smallest unit of the model. These HRU's are areas of the watershed that have uniform hydrologic responses. Helotes Creek watershed HRU's are segmented according to slope, vegetation type, elevation, and aspect. Model inputs include several time-series datasets. Precipitation, temperature, dew-point temperature, and vapor pressure were acquired from PRISM Climate Group (Section 2.5.1), which provides modeled climate data for the conterminous United States. Surface shortwave radiation data were downloaded from the North American Land Data Assimilation System (NLDAS).

The model was calibrated to streamflow measurements from the Helotes Creek USGS gage 08181400 for close to a 3-year period, 01-01-2016 to 11-01-2018. The model was validated, or tested, over a 2-year period, 01-01-2014 to 12-31-2015. **Table 4-1** shows the percentage of rainfall in the system that partitioned into evapotranspiration, runoff to streamflow, and groundwater recharge.

Table 4-1 Components of the water balance normalized to rainfall over the calibration and validation periods.

Water Balance Components	Calibration	Validation
Actual Evapotranspiration	72.67%	77.10%
Recharge	13.48%	10.20%
Runoff	13.85%	12.60%

The model calibration is considered average, with simulated streamflow matching observed streamflow with an R^2 value of 0.58 over the calibration period and 0.614 over the validation period. **Figure 4-1** and **Figure 4-2** show the results of the streamflow calibration and validation.

The lack of detailed data specific to the Helotes Creek watershed is a limitation in the model. For instance, vegetation and soils inputs were mapped at a large scale with insufficient resolution to represent variation within the watershed. Also, a major assumption was that there was no withdrawal of streamflow for private usage. This is likely false, yet it was not possible or feasible to thoroughly examine the streams for evidence to the contrary. Additionally, karst features such as swallets or other discrete recharge features are not known nor were they accounted for in the model. This would explain why the model consistently over-predicts streamflow volumes at the gage as it is not able to account for streamflow losses. Overall, the calibrated PRMS model is considered adequate for the purpose of providing reasonable numerical representations of watershed properties in the integrated hydrologic model.

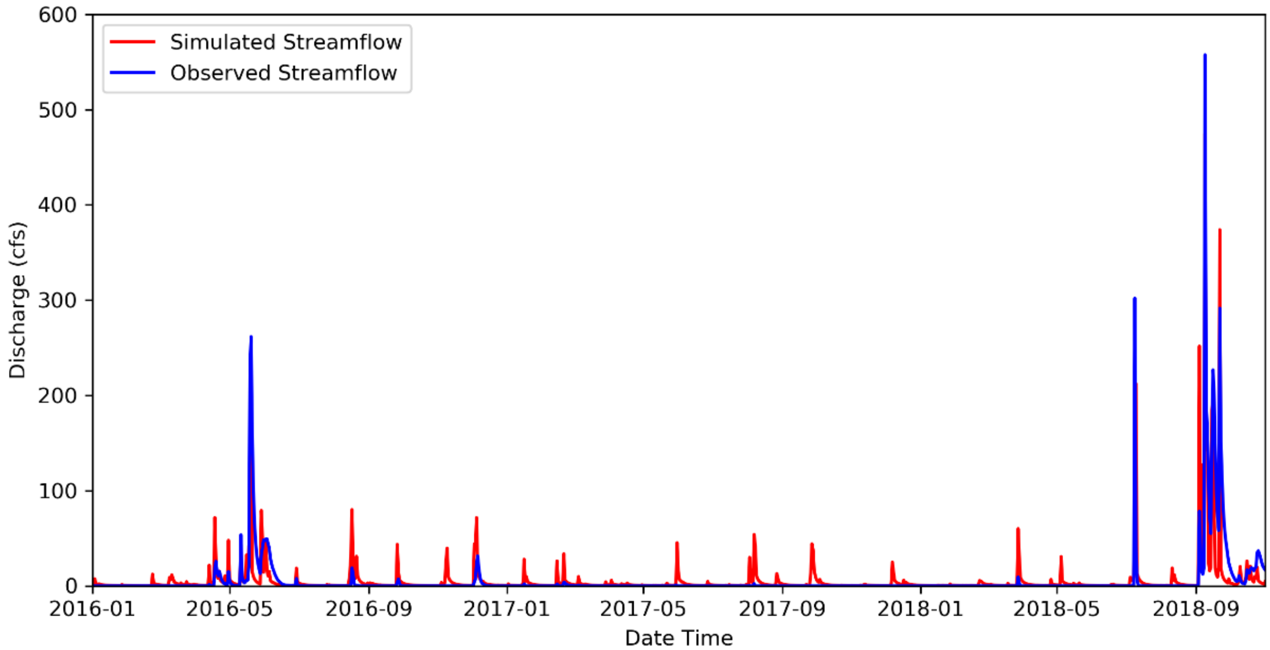


Figure 4-1 Observed and simulated discharge measured at Helotes Creek gage for the 3-year calibration period.

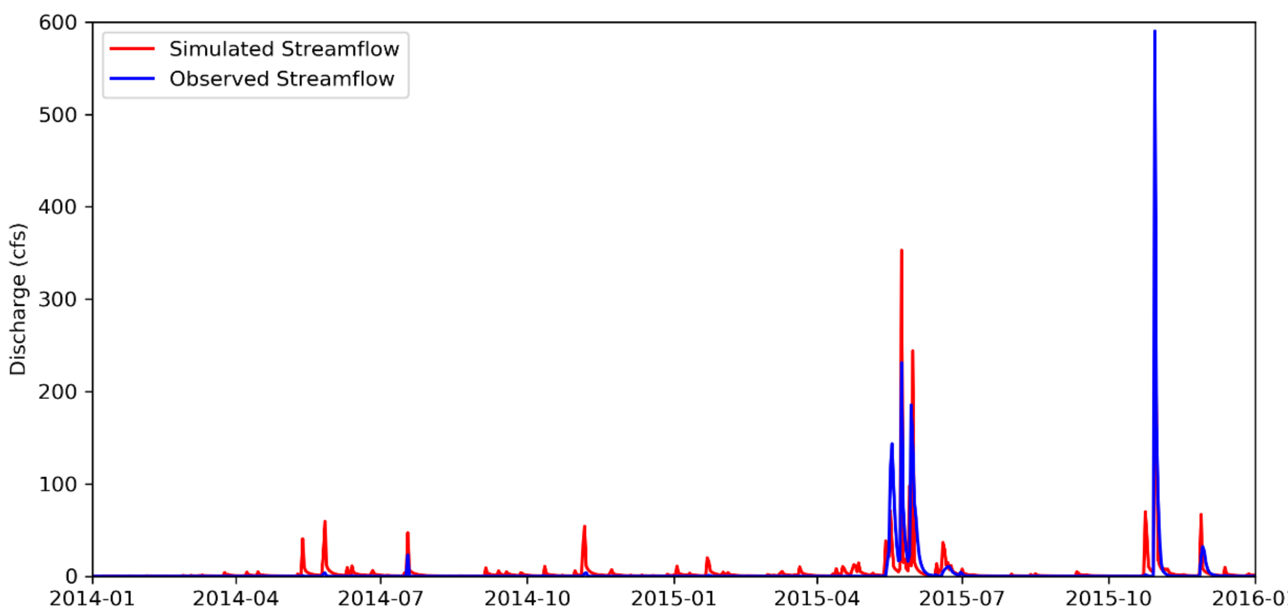


Figure 4-2 Observed and simulated discharge measured at Helotes Creek gage for the 2-year validation period.

4.2.2 GSFLOW Model Implementation

Previous groundwater models have been developed at a large scale for the San Antonio segment of the Edwards Aquifer. Lindgren et al. (2004) with the USGS and Lindgren (2006) created what is considered the original Edwards Aquifer groundwater model for the San Antonio segment using MODFLOW-2000. The 2004 version of the model used two hydraulic conductivity distributions to incorporate matrix and conduit flow to accommodate the karstic nature of the aquifer. The groundwater model developed by Lindgren (2006) was constructed without explicit regard for conduits and relied solely on diffuse flow. These two original Edwards Aquifer models were updated in the South-Central Texas TANC study (Lindgren et al., 2011) expanding the hydraulic conductivity parameterization in both the vertical and horizontal directions.

In 2015, LimnoTech attempted to adapt and link the 2004 MODFLOW (Lindgren et al., 2004) and the LBG-Guyton 2005 HSPF model to evaluate the benefits of the EAPP protected lands. They were able to implement the HSPF model but unable to link it with the groundwater model. This attempt also lacked implementation of solute-transport modeling. The study limited itself to reporting on the potential impacts of full development on land protected by the EAPP and compared the potential impacts to current development.

The primary goal in designing an integrated hydrologic model for Helotes Creek watershed was to accurately capture transport of solutes associated with wastewater into Edwards Aquifer receiving units. As such, model parameterization and calibration approaches prioritized constraining and accurately simulating conceptualized pathways. The integrated hydrologic model was developed in GSFLOW 2.1.0 (Regan & Niswonger, 2020). A full description of the model including inputs and results can be found in the GSFLOW Appendix.

Because most of the Helotes Creek watershed is located in the contributing zone of the Edwards Aquifer, flow pathways that first pass through Trinity units are important potential routes for solute delivery to the Edwards Aquifer. The only observation data available for calibration were target water levels in four Lower Glen Rose wells and stream gage data, so the only materials with calibrated hydrologic properties were the Lower Glen Rose throughout the model domain and the materials directly underlying stream reaches.

There are many faults within the model domain. The model does not represent faults as a unique material type, but faults are implicitly represented in the framework model in the form of offsets in material types. For example, the model allows for flow between confined Trinity and confined Edwards units where these conductive units are juxtaposed at the Haby Crossing Fault, forming the primary entry zone into the confined Edwards units.

The Cavernous Glen Rose just upstream of the USGS gage is included in the model as a highly conductive losing reach, based on (i) wet and dry reaches observed in field surveys and (ii) gaining and losing reaches described in a literature review. The model represents this losing reach as the primary entry point for wastewater effluent discharged to streams to infiltrate into transmissive Trinity units upgradient of the Haby Crossing Fault.

Potential groundwater-transport pathways are delineated with subsurface particles tracked from postulated groundwater entry points to a surface discharge point or to the model boundary. Particle tracking was performed using the MODPATH 7.2.001 (United States Geological Survey, 2017) software with steady-state flows calculated by MODFLOW. Streamflow pathways are not explicitly represented; instead, particles are introduced to the groundwater at the stream bed in the losing reach of the Cavernous Glen Rose just upstream of the USGS gage.

Adding wastewater facilities to the Helotes Creek watershed alters the water budget to some extent, but the potential changes are installation-specific and any additional discharge water is likely to be small compared to the existing flows in the system. Therefore, even though additional discharge may cause local changes to the flow fields, the assumption is that these would not have such a large effect on flow fields in the streams and subsurface that the discharge point for the transport pathways would be significantly affected. This is reasonable because (i) the Helotes Creek watershed is small compared to the upstream recharge area for the transmissive Trinity units and (ii) flows during runoff events are much larger than postulated changes in surface releases. Accordingly, every transport scenario uses flow fields that are calculated with the current water budget.

4.2.3 Solute Transport from OSSF's

Mass loading from OSSF releases is applied to the subsurface directly beneath facilities. In our conceptual model, transport from OSSFs to the Edwards Aquifer is through a subsurface pathway, passing through transmissive hydrostratigraphic Trinity units into transmissive hydrostratigraphic Edwards units where the transmissive units are juxtaposed.

Land-surface areas with a high OSSF density were delineated with polygons. All OSSFs in the Helotes Creek watershed were assigned to a polygon based on proximity. MODPATH-tracked particles were released from every land-surface grid cell on the perimeter of each OSSF polygon, as well as all land-surface grid cells lying on selected grid rows and columns crossing through each polygon, using flow results from a steady-state simulation of the parameterized model. The set of calculated pathways represent the range of potential pathways for solute transport in the saturated zone.

Figure 4-3 shows the (i) OSSF areas, (ii) inflow zone extents for zone-budget analysis, and (iii) resulting flow pathways in plan view. Almost all paths eventual cross into the Edwards unit, with a few paths surfacing in Helotes Creek where the Cavernous Glen Rose is exposed in the reach immediately upstream of the stream gage location. Some of the stream discharge paths may reenter the subsurface in losing reaches further downstream, but MODPATH terminates tracking at the initial discharge point.

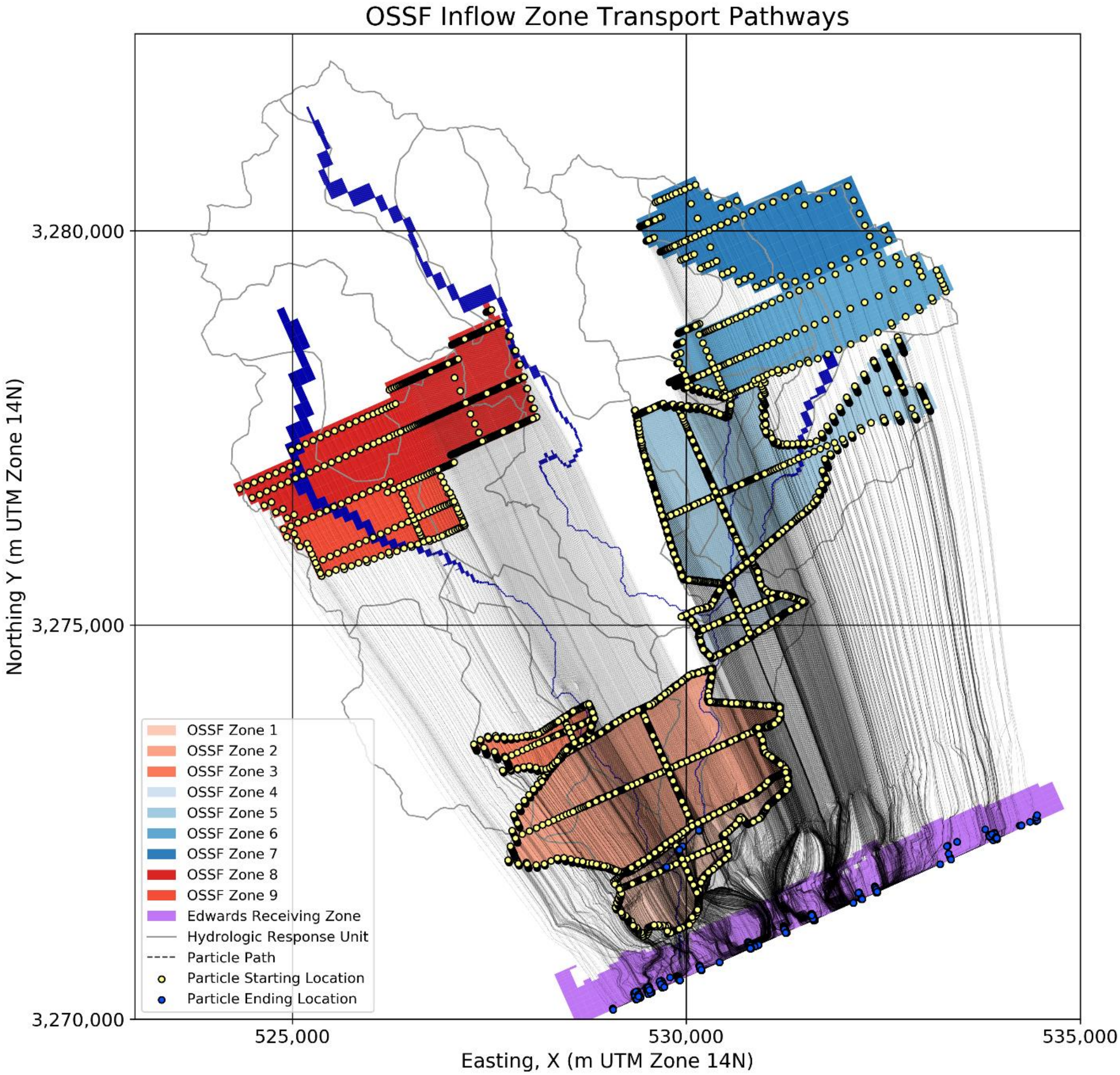


Figure 4-3 Results of a MODPATH particle tracking simulation for OSSF Inflow Zones.

Steady-state flows calculated by the parameterized integrated hydrologic model for the Helotes Creek watershed. OSSF regions that flow into the Western transport pathway are shown in red and those that flow into the Eastern transport pathway are shown in blue. The Edwards Aquifer receiving zone is shown in light purple. Particle transport pathlines are shown with faint black lines, with the particle starting and ending locations shown with yellow and blue circles, respectively.

4.2.4 Solute Transport from TLAP Facilities

Mass loading from TLAP facilities might occur as (i) injection into the shallow subsurface or (ii) aerial dispersal over the land surface. Both release scenarios were simulated for two potential TLAP facility locations along stream reaches, using separate simulations for each facility and release scenario.

In all scenarios, the conceptualized pathway into the Edwards Aquifer is groundwater flow through transmissive hydrostratigraphic Trinity units that are juxtaposed with transmissive hydrostratigraphic Edwards units, but the entry mode to the Trinity units differs among scenarios. In the subsurface injection scenario, releases are modeled as direct injection into hydrostratigraphic Trinity units at the source location. In the aerial dispersion scenario, released solutes are first transported to streams as runoff, then the solutes infiltrate from the streambed along downstream losing stream reaches.

4.2.4.1 TLAP Subsurface Injection

Subsurface release is conceptualized as the result of vertical flow from the very shallow subsurface (~ 48 inches deep) to the aquifer. For each site, this process was represented as particle injection into the uppermost grid cell in each grid column within the hypothesized TLAP facility footprint. The collection of pathways in **Figure 4-4** suggests that regional flow would tend to carry subsurface releases into the Edwards Aquifer recharge zone.

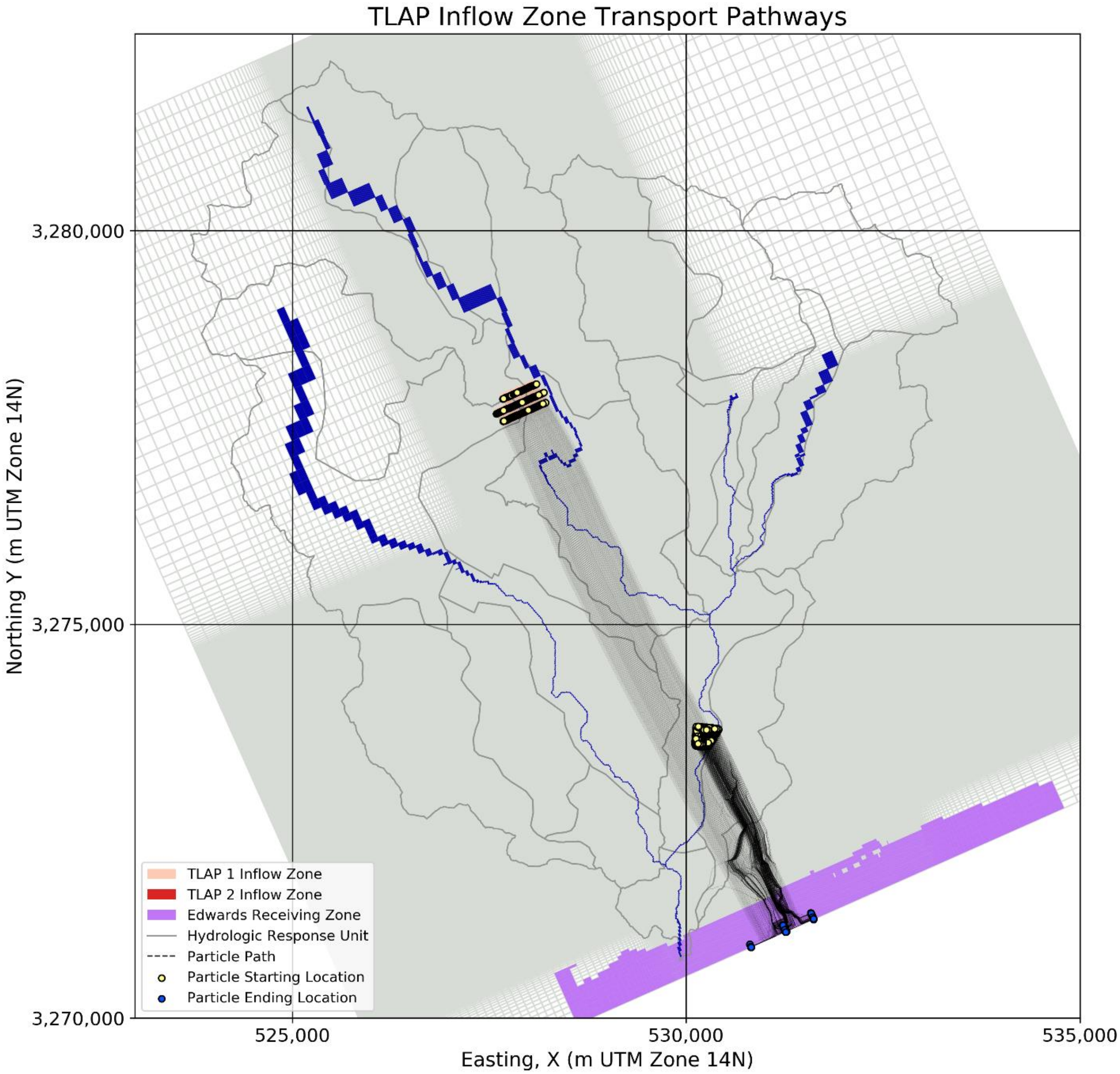


Figure 4-4 Results of a MODPATH particle tracking simulation for direct subsurface injection from TLAP facilities.

Steady-state flows calculated by the parameterized integrated hydrologic model for the Helotes Creek watershed. Both TLAP areas flow into the Western transport pathway. The Edwards Aquifer receiving zone is shown in light purple. Particle transport pathlines are shown with faint black lines, with the particle starting and ending locations shown with yellow and blue circles, respectively.

4.2.4.2 TLAP Aerial Dispersal

Subsurface release subsequent to TLAP aerial dispersal is conceptualized as the result of (i) runoff carrying solutes into streams, (ii) streamflow subsequently infiltrating into the subsurface in losing reaches, (iii) direct infiltration to the surface at the point of application. This process was represented as particle injection into the uppermost grid cell in each grid column along the streambed in the losing reach where the Cavernous Glen Rose crops out upstream of the USGS gage. The collection of pathways represents the set of potential injection points, all upgradient of the Haby Crossing Fault. The collection of pathways in **Figure 4-5** suggests that regional flow would tend to carry subsurface releases into the Edwards Aquifer recharge zone.

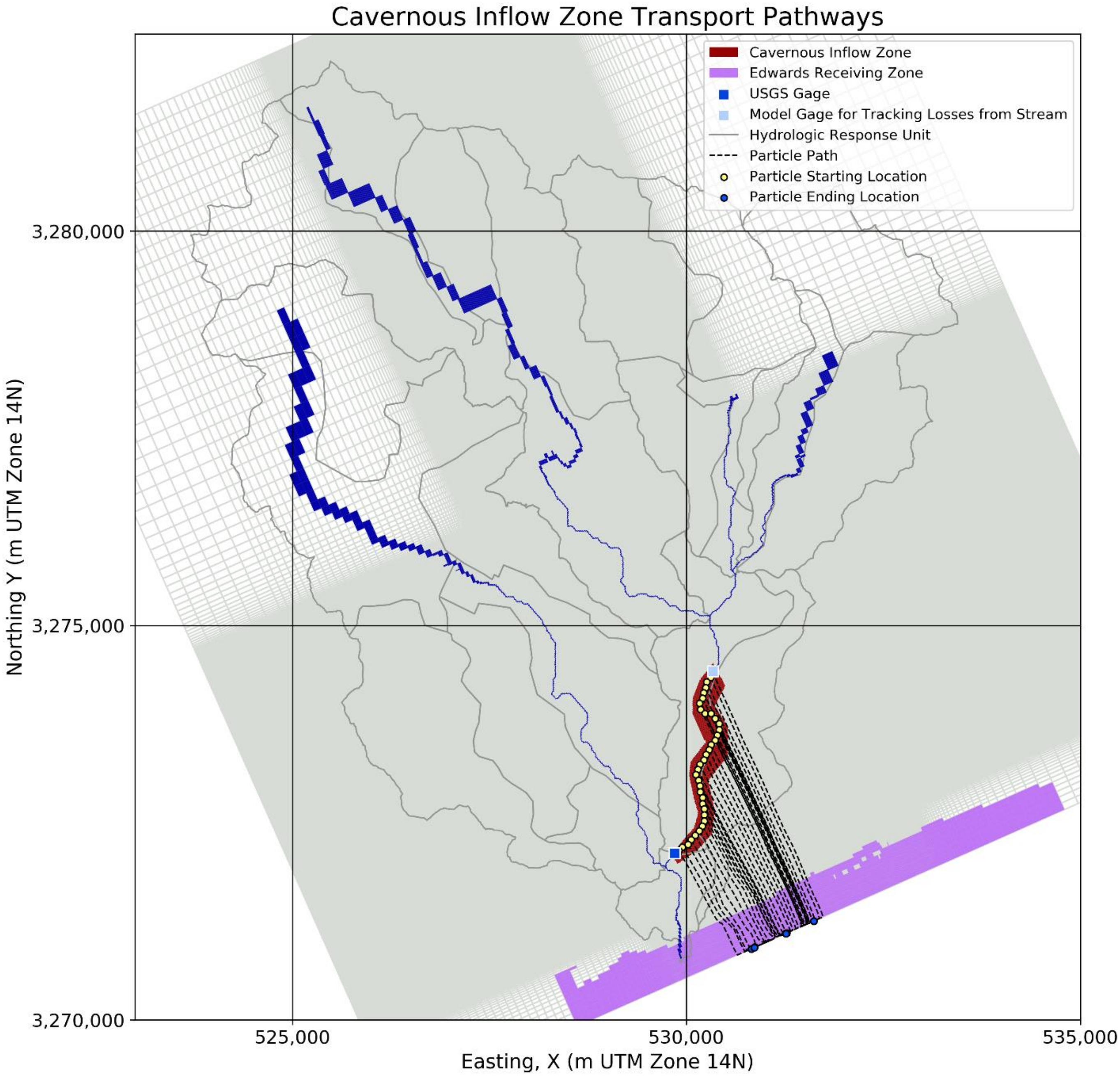


Figure 4-5 Results of a MODPATH particle tracking simulation for particles from TLAP facilities entering the Cavernous inflow zone.

Steady-state flows calculated by the parameterized integrated hydrologic model for the Helotes Creek watershed. The zone where cavernous material underlies the streambed that flows into the Western transport pathway is shown in red and the Edwards Aquifer receiving zone is shown in light purple. Particle transport pathlines are shown with faint black lines, with the particle starting and ending locations shown with yellow and blue circles, respectively.

4.2.5 Solute Transport from TPDES Facilities

TPDES facilities discharge treated effluent directly to streams during times of flow. The conceptualized pathway to the Edwards Aquifer for effluent from TPDES facilities is discharge directly to streams where infiltration into transmissive hydrostratigraphic Trinity units in the streambed occurs, followed by transport through transmissive hydrostratigraphic Trinity units that are juxtaposed with transmissive hydrostratigraphic Edwards units. This conceptualized pathway into the subsurface is similar to that of TLAP Aerial Dispersal (**Figure 4-5**); therefore, the MODPATH analysis would be identical for the two types of facilities.

Any differences in transport characteristics between TPDES facilities and TLAP facilities would arise from the timing and magnitude of loading to the stream. TLAP releases are expected to occur in infrequent pulses during large episodic runoff events, while TPDES releases are expected to occur over a wider range of flows. The spatial patterns of groundwater pathways may not be strongly affected by these differences, but the fraction of streamflow lost to the groundwater is likely to be smaller under high flows than under normal flows. Accordingly, the fraction of TLAP releases entering the subsurface is likely to be smaller than the fraction of TPDES releases.

4.2.6 Volumetric Flow Rates through Transport Pathways

ZONEBUDGET 3.01 software (United States Geological Survey, 2009) was used to constrain volumetric flow rates between successive mixing reservoirs located along the transport pathway from each inflow zone to the Edwards Aquifer recharge zone. Many of the solute inflow zones identified above are located in close proximity to one another and thus share significant portions of their transport pathway to the Edwards Aquifer recharge zone with other inflow zones. Two three-dimensional combined transport pathways were identified that fully contain all inflow zones and enclose all modeled flow pathways from MODPATH analysis. Together, the two transport pathways account for the transport of all mass loading from Helotes Creek watershed to the Edwards Aquifer receiving body. Both transport pathways are illustrated in plan view in **Figure 4-6**.

The Western transport pathway is split into five mixing reservoirs: W1, W2, W3, W4, and W5. This pathway encloses the Cavernous Inflow Zone, both TLAP Facility Inflow Zones, and OSSF Inflow Zones 1, 2, 3, 8 and 9. The Eastern transport pathway is also split into five mixing reservoirs: E1, E2, E3, E4, and E5. This pathway encloses OSSF Inflow Zones 4, 5, 6, and 7. Inflow zones have a thickness of one layer and are located at the top cell in each vertical column with a positive head value in the steady state simulation. Pathway zones were delineated using polygons in plan view, which were identified by the highest and lowest layers through which transport occurred in each zone. Each zone included all finite-difference cells with a positive head value in the steady-state simulation between the highest and lowest layer for each vertical column in the polygon. The Edwards Aquifer receiving body was delineated as all finite-difference cells south of the Haby Crossing Fault with an Edwards Formation material code. The connection of the final zone in each pathway (E1 and W1) with the Edwards Aquifer was forced by including the cells, within a given layer, between the final pathway zone and the Edwards Aquifer material zone as part of the final pathway zone. The vertical extent of inflow zones and the pathway zones for both pathways are detailed in **Figure 4-7.**

ZONEBUDGET analyses with these zones were executed for the three-year period from January 1st, 2013 – December 31st, 2015. Net inflows to and between each reservoir were calculated at monthly time steps and used to inform transport modeling.

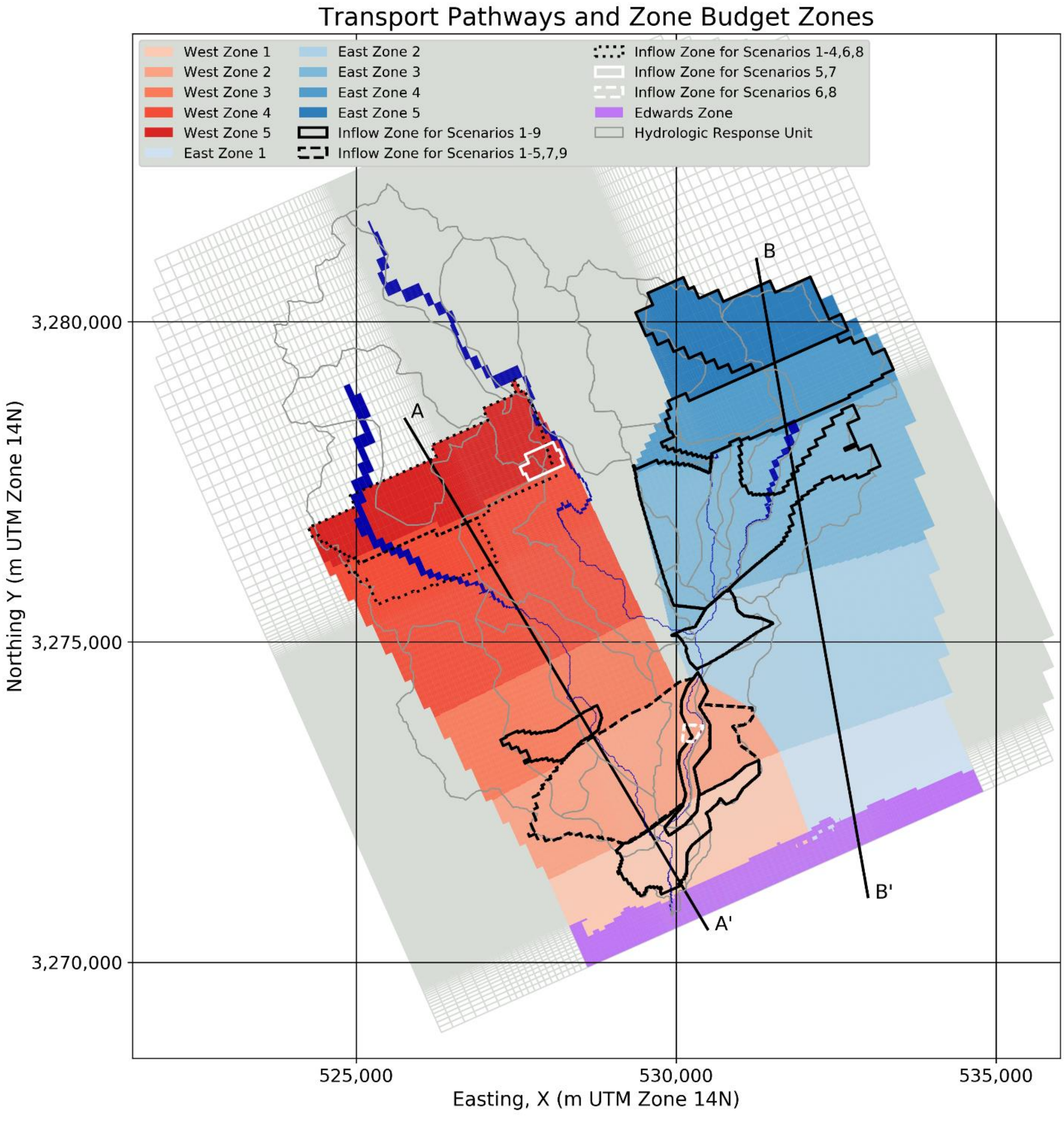
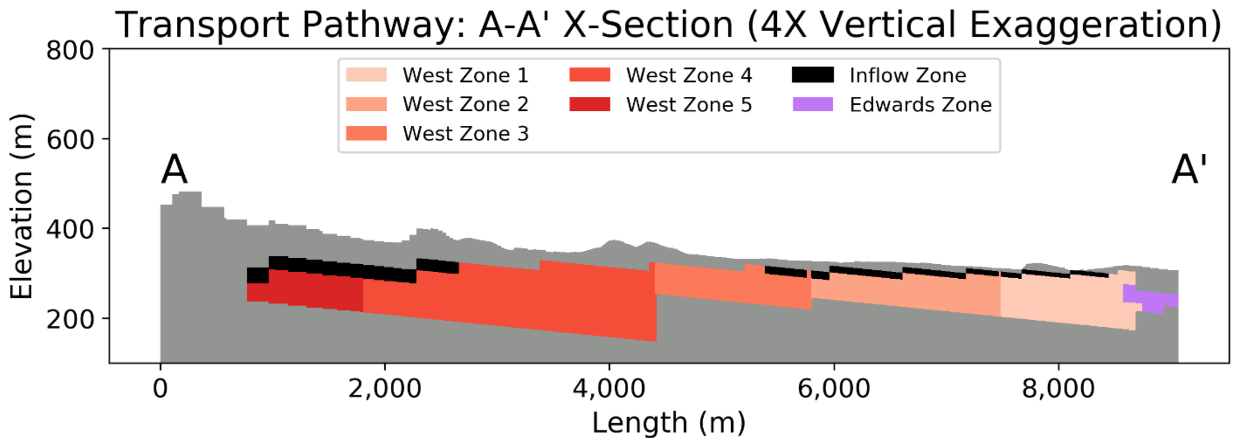


Figure 4-6 Budget zones delineating Western and Eastern transport pathways as determined from MODPATH particle tracking analysis.

The transport zones encompassing the Western transport pathway are shown in red and transport zones encompassing the Eastern transport pathway are shown in blue. Inflow zones from OSSF's, TLAP facilities and stream infiltration through transmissive Cavernous material are shown with solid, dashed or dotted black and white outlines to indicate which scenarios they correspond to. The Edwards Aquifer receiving zone is shown in light purple. Sections for cross-section lines A-A′ and B-B′ are shown in Figure 4-7



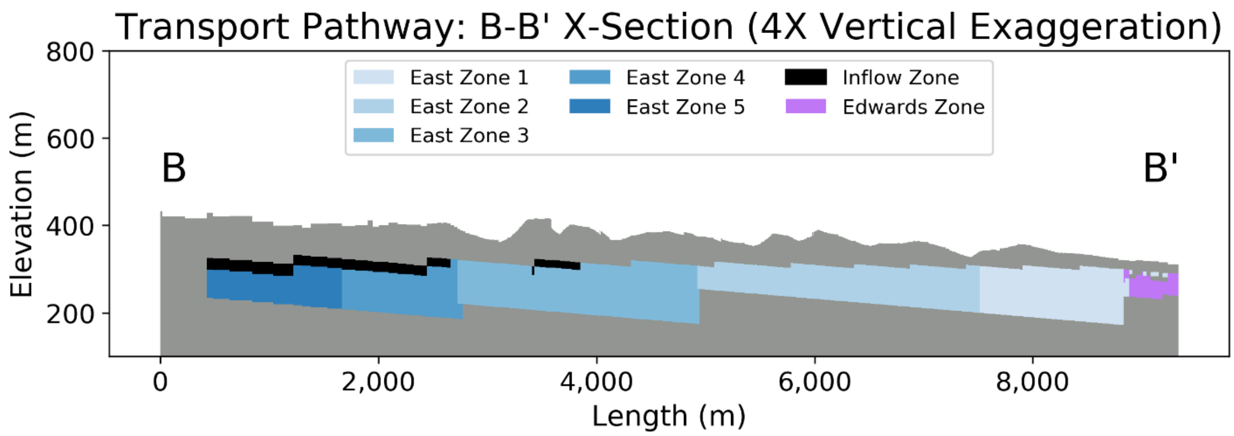


Figure 4-7 Cross-sections detailing the vertical extent of inflow and transport budget zones in the Western (A, red) and Eastern (B, blue) transport pathways.

The inflow budget zones are shown in black. The Edwards receiving zone is shown in light purple.

4.3 Transport Model Implementation

Previous work in similar watersheds regarding environmental impact modeling has been conducted by the City of Austin, utilizing the Water Quality Analysis Simulation Program (WASP), a U.S. Environmental Protection Agency program to assess potential water-quality impacts of proposed wastewater disposal facilities. The model allows for simulations of nutrient loading into surface water and simulates the effect on the trophic state of Onion Creek (Richter, 2016).

GoldSim 12.1 was used to perform solute-transport simulations in lieu of a mechanistic advection-dispersion simulator. Given the scope of the project objectives and the limited understanding of conduit/diffusive flow in the karstic Trinity and Edwards aquifers, the use of GoldSim was determined to be justified.

A base model structure was created to simulate volume and mass flows between various containers. This base model is based on the current conditions in the Helotes Creek watershed. Within this base model several pathways and components were developed:

1. **Western Pathway** (including reservoirs corresponding to the GSFLOW model zones W1 through W5, OSSF zones 1, 2, 3, 8, and 9, and the TLAP zones)
2. **Eastern Pathway** (including reservoirs corresponding to the GSFLOW model zones E1 through E5 and OSSF zones 4 through 7)
3. **Cavernous** – a portion of the Helotes Creek stream segment, corresponding to the GSFLOW zone of the same name
4. **The quarry** south of the Helotes Creek watershed
5. **Edwards Aquifer recharge zone** (the point of analysis, not including the quarry)
6. **Edwards Aquifer artesian zone** (as a placeholder container to which all the flow from the model's recharge zone is directed)

Within each model component listed above, a series of reservoir elements serving as continuously-stirred batch reactors were created to link the different zones to correspond to the zones noted in **Figure 4-6** and **Figure 4-7**. A series of volume (water) and mass-batch reactors were created within each pathway in a form of mass-water pairing, due to the dependence of mass calculations on the volumes.

Average simulated flow values from the GSFLOW model were implemented to reflect flow between the different zones. Expression elements were incorporated to include the equations pertinent to the transport modeling, which are listed below.

Total OSSF effluent flow per polygon was determined by:

$$Eff_{OSSFs} = Eff_{standard} * n$$

where $Eff_{standard}$ is the assumed standard effluent flow issued from an OSSF (680 L/day) and n is the number of OSSFs estimated to be contained within the polygon. Mass rates loading to the OSSF zones were calculated by:

$$MR = C * Eff_{OSSFs}$$

where C is the assumed total nitrogen concentration in the OSSF effluent (40 or 80 mg/L) and Eff_{OSSFs} is the calculated effluent flow per OSSF zone.

Mass outflows from each OSSF reservoir were determined by:

$$M_{OSSFs,out} = (M_{OSSF}/V) * (V_{WR} + V_{OR})$$

where M_{OSSF} is the mass in the reservoir, V is the volume of the corresponding Volume reservoir, and V_{WR} and V_{OR} are the withdrawal rates and overflow rates of the corresponding Volume reservoirs, respectively.

Concentrations for the non-OSSF mass reservoirs were calculated from:

$$C_W = M_W/V_W$$

where M_w is the mass of the given reservoir and V_w is the volume of the corresponding Volume reservoir.

Mass outflows from each non-OSSF mass reservoir were determined by:

$$M_{W,out} = C_W * (V_{WR} + V_{OR})$$

The Cavernous pathway included additional equations to account for non-point mass loading of total nitrogen, particularly during stormflow. The general non-point loading equation considered for this purpose was based on an equation determined by Zhu and Glick (2017) for similar environments in the Austin area:

$$TN_{non-point} = -0.098 + 9.6957 * I$$

where I is the percent impervious cover of the study area, in this case the entire Helotes Creek watershed. The impervious cover for the Helotes Creek watershed estimated by the PRMS-IV model was ~3.72%. To account for the total mass loading to the runoff, the equation above was incorporated into the following equation:

$$TN_{non-point,HCW} = TN_{non-point} * R_{HCW}$$

where R_{HCW} is the average annual runoff estimated from the integrated flow model, at about 4.45 in/yr. The non-point total nitrogen concentration was determined by:

$$C_{TN,non-point} = \frac{TN_{non-point,HCW}}{(R_{HCW} * A)}$$

where A is the area of the Helotes Creek watershed.

The Quarry

The Quarry pathway does not have a corresponding GSFLOW zone and is represented solely in the GoldSim models as a plug-flow reactor pair. In order to account for the fact that streamflow from the Helotes Creek watershed usually only reaches the quarry and Edwards Aquifer recharge zone during and following storm events, a rating curve based on the USGS stream gage data was generated to select a likely gage height and streamflow rate that would be representative of storm conditions. In this case, 97.4 cfs was selected as a reasonable threshold for flow to make it down to the quarry area.

The recharge zone container was similar to the other pathways, with the reservoirs volume estimated by calculating the volume of the cells from the flow model that corresponded to units that form the recharge zone. Both the Cavernous and recharge zone pathways were equipped with Material Delay elements to account for their role as flow-through components for the Helotes Creek volume and mass to reach the artesian zone.

Recharge Zone and Artesian Zone

The recharge zone was selected as the point of analysis. Similar to the quarry, it is represented by a plug-flow reactor pair and was derived separately from the GSFLOW model. The outflows from the recharge zone were directed to an arbitrary artesian-zone reactor pair.

A separate GoldSim model was created for each of the solute-transport scenarios discussed in Section 3. The average simulated flows used for the Base Case model were updated accordingly to represent the different scenarios. Other modifications made to the Base Case model structure in order to accommodate Scenarios 1 through 8 are briefly described below. **Figure 4-8** through **Figure 4-11** are schematics representing the different models.

4.3.1 OSSF Scenarios

Scenarios 1 through 3 required simple modifications. For Scenario 1, the number of OSSFs for relevant OSSF reservoirs was updated to reflect the increase caused by the inclusion of potential non-registered OSSFs. Scenario 2 required accounting for 13% of the OSSFs as malfunctioning. This required updating the mass-rate equations to the following:

$$MR = (C_{OSSFs} * (Eff_{OSSFs} * \ 0.87)) + (C_{OSSF,malf} * (Eff_{OSSFs} * \ 0.13))$$

where C_{OSSFs} and $C_{OSSF,malf}$ are total nitrogen concentrations in the effluent of functioning and failing OSSFs, respectively; whereas 0.87 and 0.13 are the fractions of functioning and malfunctioning OSSFs per OSSF zone, respectively.

Scenario 3, like Scenario 1, simply required updating the number of OSSFs for the relevant OSSF reservoirs to reflect a 15% increase in the number of OSSFs due to increased population and development.

4.3.2 TLAP Scenarios

Developing the TLAP Scenarios (4 through 7) consisted of replacing specific OSSF reservoirs and their associated expression and data elements with the TLAP reservoirs and associated elements. For Scenarios 4 and 6, OSSF reservoirs 8 and 9 and their associated elements were replaced by a TLAP reservoir representing the northern TLAP. For Scenarios 5 and 7, OSSF reservoir 2 and its associated elements were replaced by a TLAP reservoir representing the southern TLAP. The TLAP surface spray Scenarios (6 and 7) also involved creation of additional elements to partition part of the effluent flow to the subsurface and part of the effluent flow to runoff.

4.3.3 TPDES Scenario

For Scenario 8, the elements associated with OSSF zone 2 were removed. Elements associated with the hypothetical TPDES facility were linked so that the flow would contribute to the Cavernous reservoir.

In order to determine the equilibrium or asymptotic values for mass loading, the model simulation settings were adjusted to run and report for 10,000 years at 10-year increments. However, given the limitations described in Sections 4.2, 5.1, and 7, this runtime is not meant to reflect the nature of transport rates or timing of mass transport.

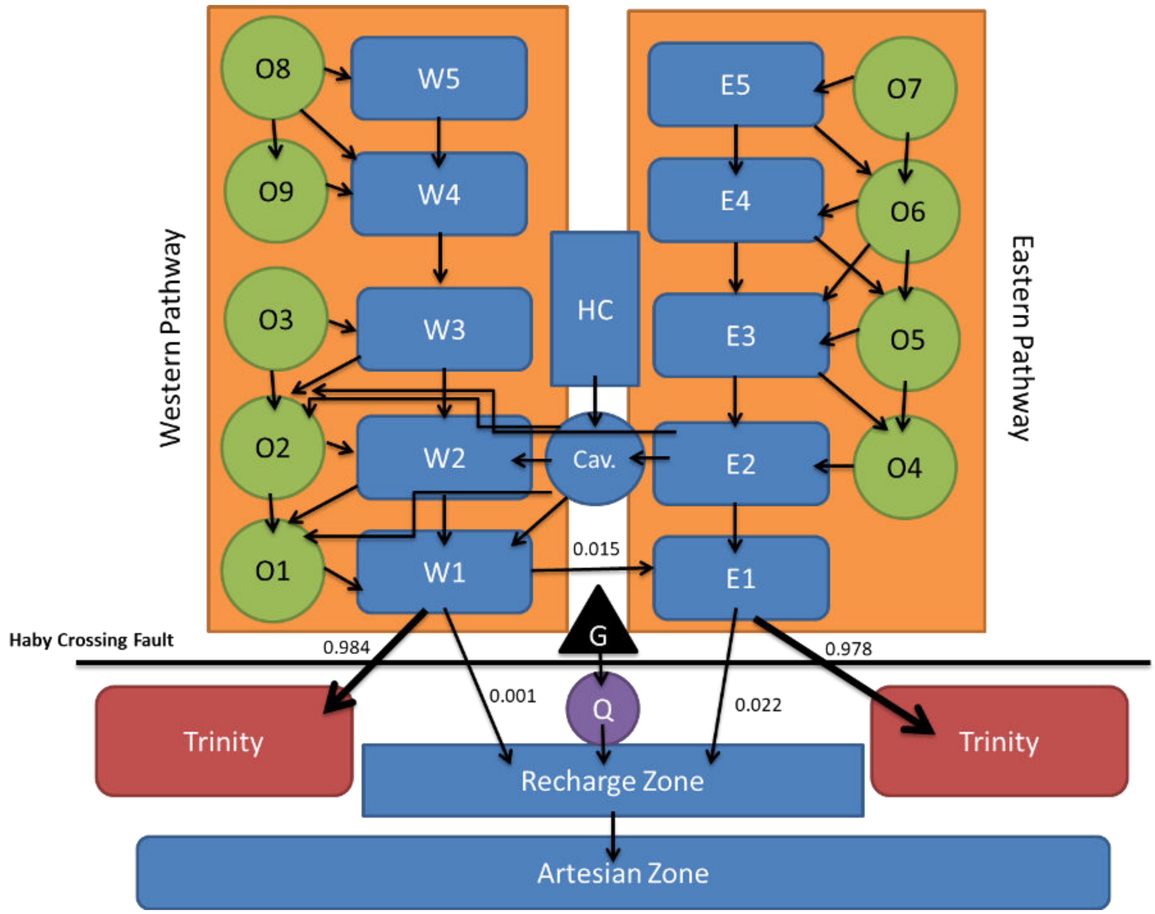


Figure 4-8 Infographic for Base Case and Scenarios 1 through 3.

Figure depicts flow within and from Western and Eastern pathways of the Helotes Creek watershed (noted by "W" and "E" elements) across Haby Crossing Fault (dark line) to the recharge zone; OSSF and TLAP reservoirs are noted by green circles, "HC" represents Helotes Creek, "Cav." represents the Cavernous stream valley, "G" represents the USGS gage, and "Q" represents the quarry; numbers on arrows from W1 and E1 indicate fractions of flow flowing to the different downstream reservoirs.

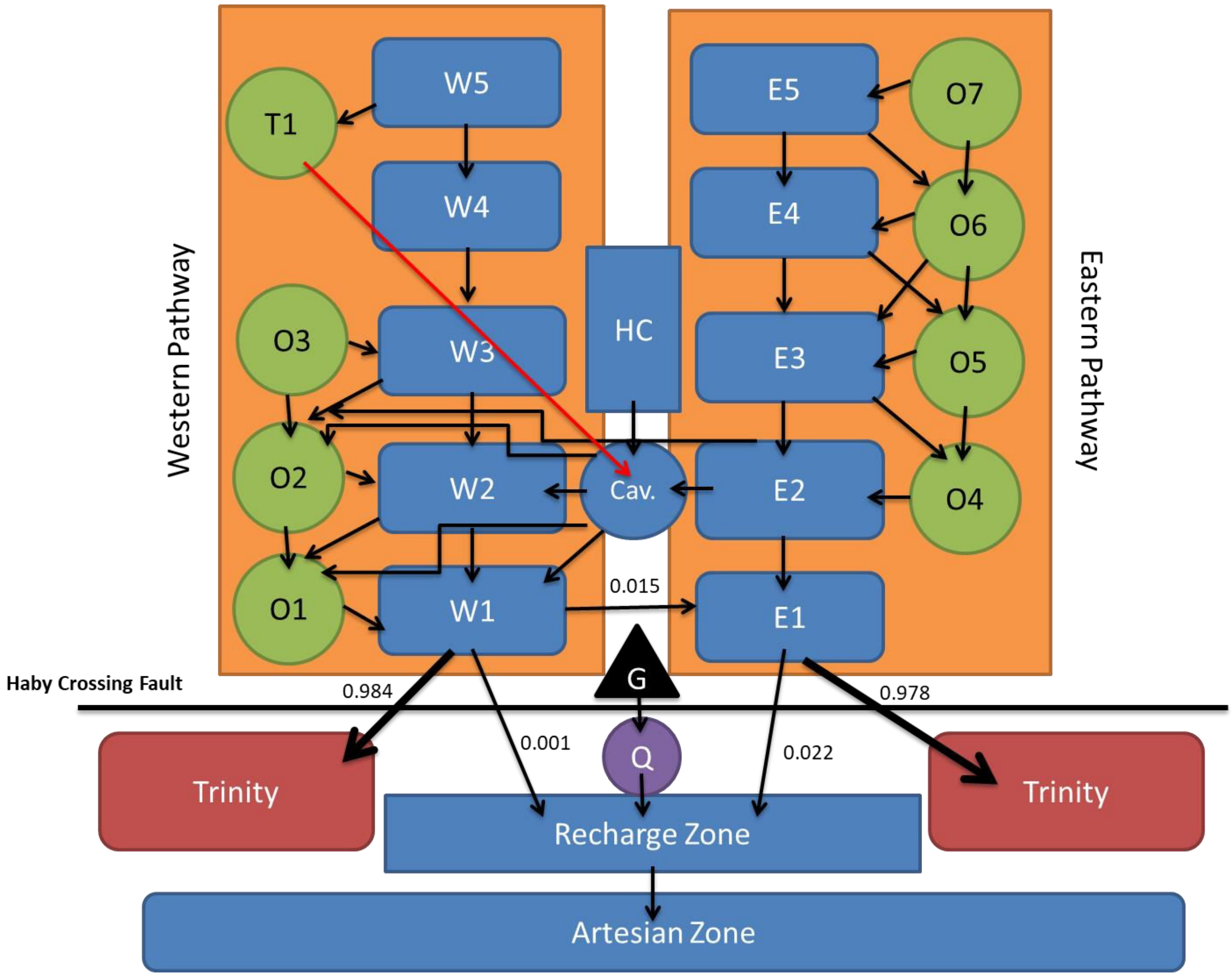


Figure 4-9 Infographic for Scenarios 4 and 6.

Figure depicts flow within and from Western and Eastern pathways of the Helotes Creek watershed (noted by "W" and "E" elements) across Haby Crossing Fault (dark line) to the recharge zone; OSSF and TLAP reservoirs are noted by green circles, "HC" represents Helotes Creek, "Cav." represents the Cavernous stream valley, "G" represents the USGS gage, and "Q" represents the quarry; the red arrow represents the TLAP effluent applied to runoff for Scenario 6; numbers on arrows from W1 and E1 indicate fractions of flow flowing to the different downstream reservoirs.

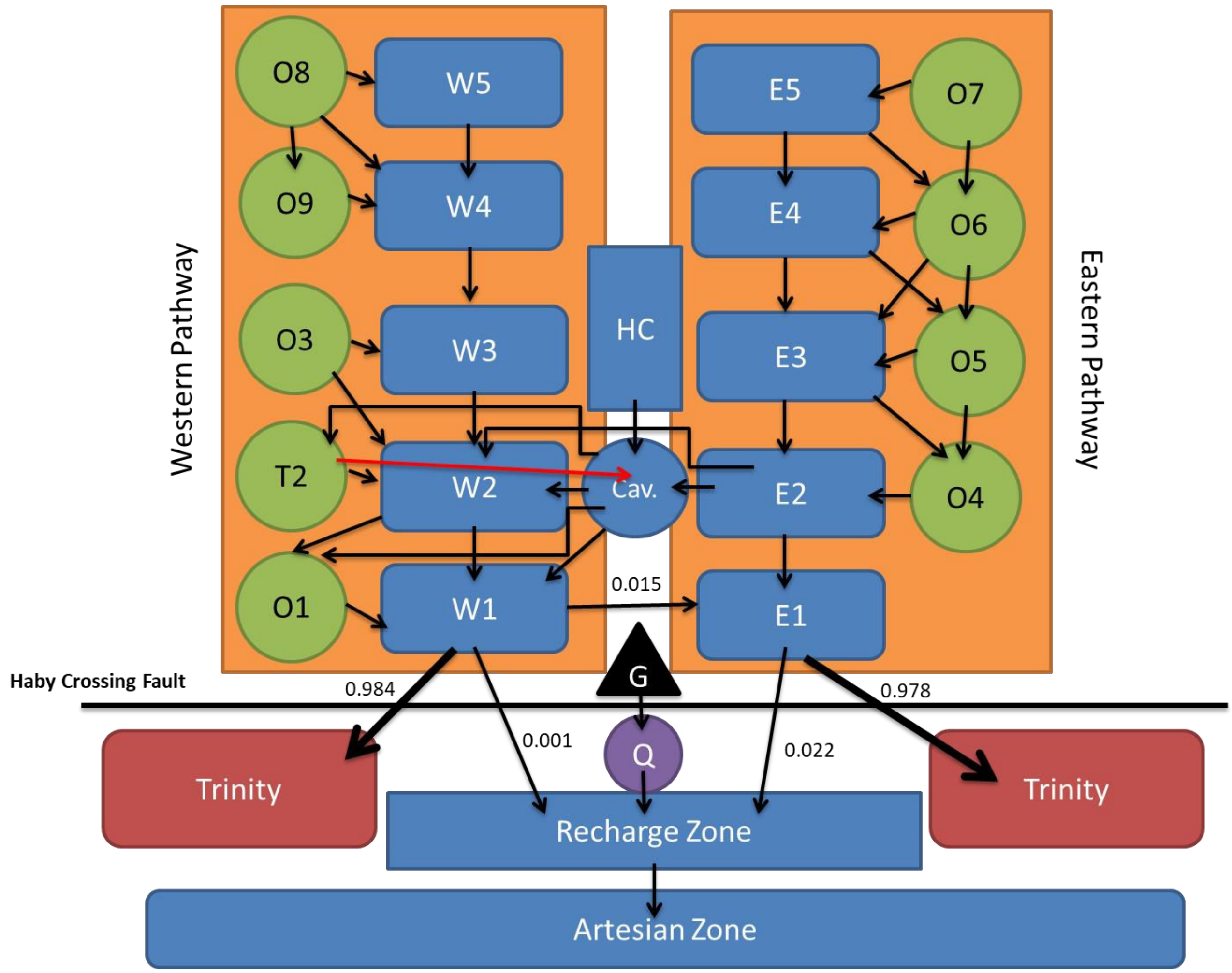


Figure 4-10 Infographic for Scenarios 5 and 7.

Figure depicts flow within and from Western and Eastern pathways of the Helotes Creek watershed (noted by "W" and "E" elements) across Haby Crossing Fault (dark line) to the recharge zone; OSSF and TLAP reservoirs are noted by green circles, "HC" represents Helotes Creek, "Cav." represents the Cavernous stream valley, "G" represents the USGS gage, and "Q" represents the quarry; the red arrow represents the TLAP effluent applied to runoff for Scenario 6; numbers on arrows from W1 and E1 indicate fractions of flow flowing to the different downstream reservoirs.

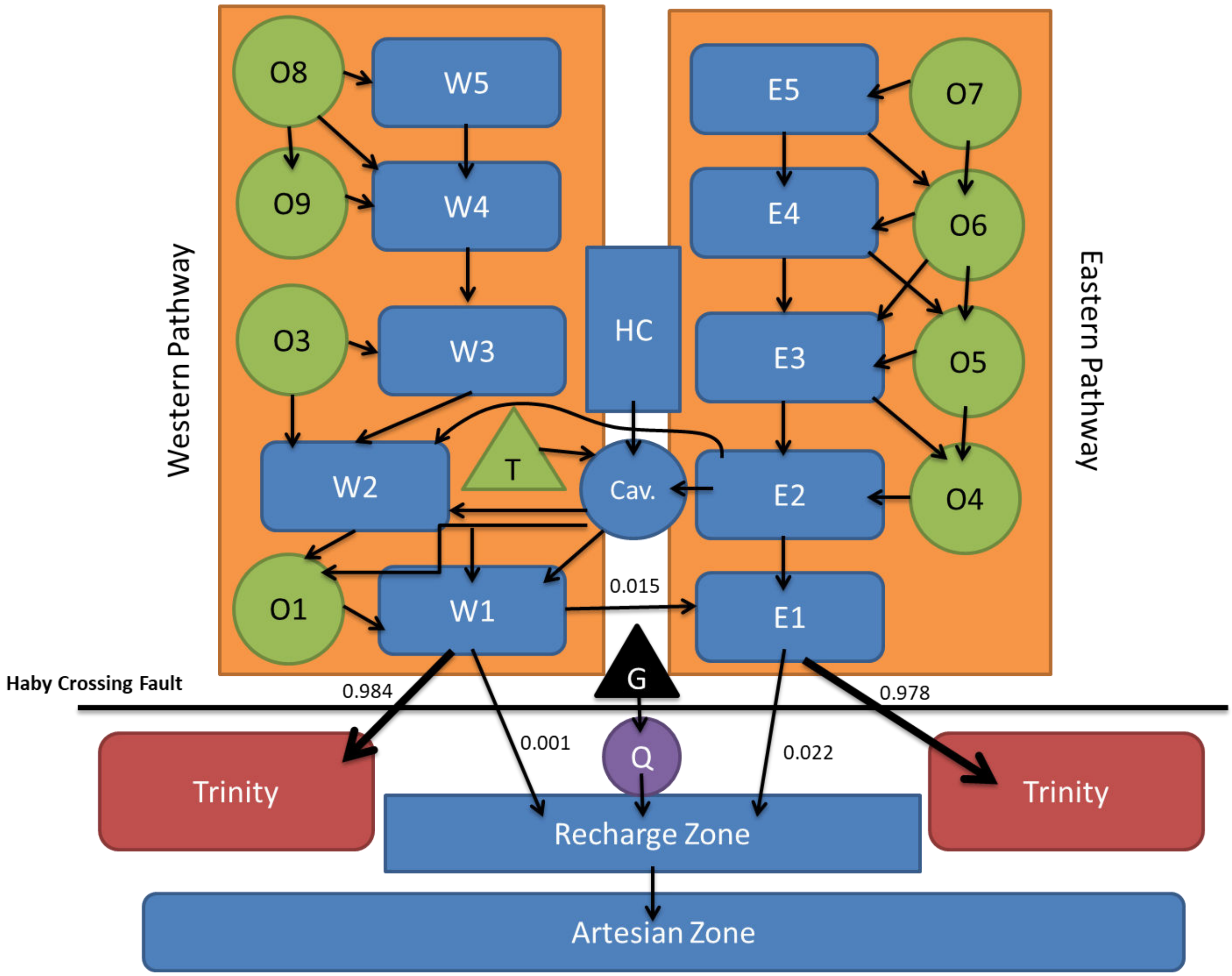


Figure 4-11 Infographic for Scenario 8.

Figure depicts flow within and from Western and Eastern pathways of the Helotes Creek watershed (noted by "W" and "E" elements) across Haby Crossing Fault (dark line) to the recharge zone; OSSF and TLAP reservoirs are noted by green circles, "HC" represents Helotes Creek, "Cav." represents the Cavernous stream valley, "G" represents the USGS gage, and "Q" represents the quarry; numbers on arrows from W1 and E1 indicate fractions of flow flowing to the different downstream reservoirs.

4.3.4 Sensitivity Analyses

Sensitivity analyses for the solute-transport modeling focused on two aspects of the models:

1. Effluent loadings and flows
2. Flow from the final watershed transport zones (W1 and E1) to the recharge zone

In the first set of sensitivity analyses, the baseline versions of Scenarios 4 and 5 were altered twice to increase the effluent flow by a factor of two. Scenario 4 alternatives 1 and 2 were assigned effluent flows of 0.560 and 0.280 MGD (versus the original 0.14 MGD), respectively. Scenario 6 alternatives 1 and 2 were assigned effluent flows of 0.100 and 0.200 MGD (versus the original 0.05 MGD), respectively. These alternatives represent extreme cases in which the maximum permitted application rate of 0.1 gal/ft^2/day is exceeded by increasing degrees. This could provide insight into how TLAP discharge scales with impacts to the recharge zone.

The second set of sensitivity analyses (**Figure 4-12)** involved changing flow from the final transport zones in the watershed to the recharge zone. This approach involved adjusting the fraction of outflow from the W1 and E1 zones that was directed to the Edwards Aquifer recharge zone versus the Trinity Aquifer units. In the Base Case model, an average fraction of 0.981 (98.1%) of flow was directed to the Trinity Aquifer, reflecting the outputs of the GSFLOW model. For the sensitivity analyses, flow directed to the recharge zone was increased to 0.25, 0.50, 0.75, and 0.981 for four tests. In this approach, the Trinity Aquifer flow system is assumed to be well-mixed, meaning all of the effluent is thoroughly distributed in the Trinity Aquifer flow. This results in progressively increased cumulative masses to the recharge zone, with uniform concentration due to the mass loading being dependent on the flow contribution to the Edwards Aquifer. **Table 4-2** summarizes the fractions used to partition the flow for the Base Case and the four tests.

Table 4-2 Fractions of flow from W1 and E1 to E1, recharge zone, and Trinity Aquifer.

	Fraction of flow from Source		Target
	W1	E1	
Base Case	0.015	---	E1
	0.001	0.022	recharge zone
	0.984	0.978	Trinity
Test 1	0.015	---	E1
	0.25	0.25	recharge zone
	0.735	0.75	Trinity
Test 2	0.015	---	E1
	0.5	0.5	recharge zone
	0.485	0.5	Trinity
Test 3	0.015	---	E1
	0.75	0.75	recharge zone
	0.235	0.25	Trinity
Test 4	0.015	---	E1
	0.984	0.978	recharge zone
	0.001	0.022	Trinity

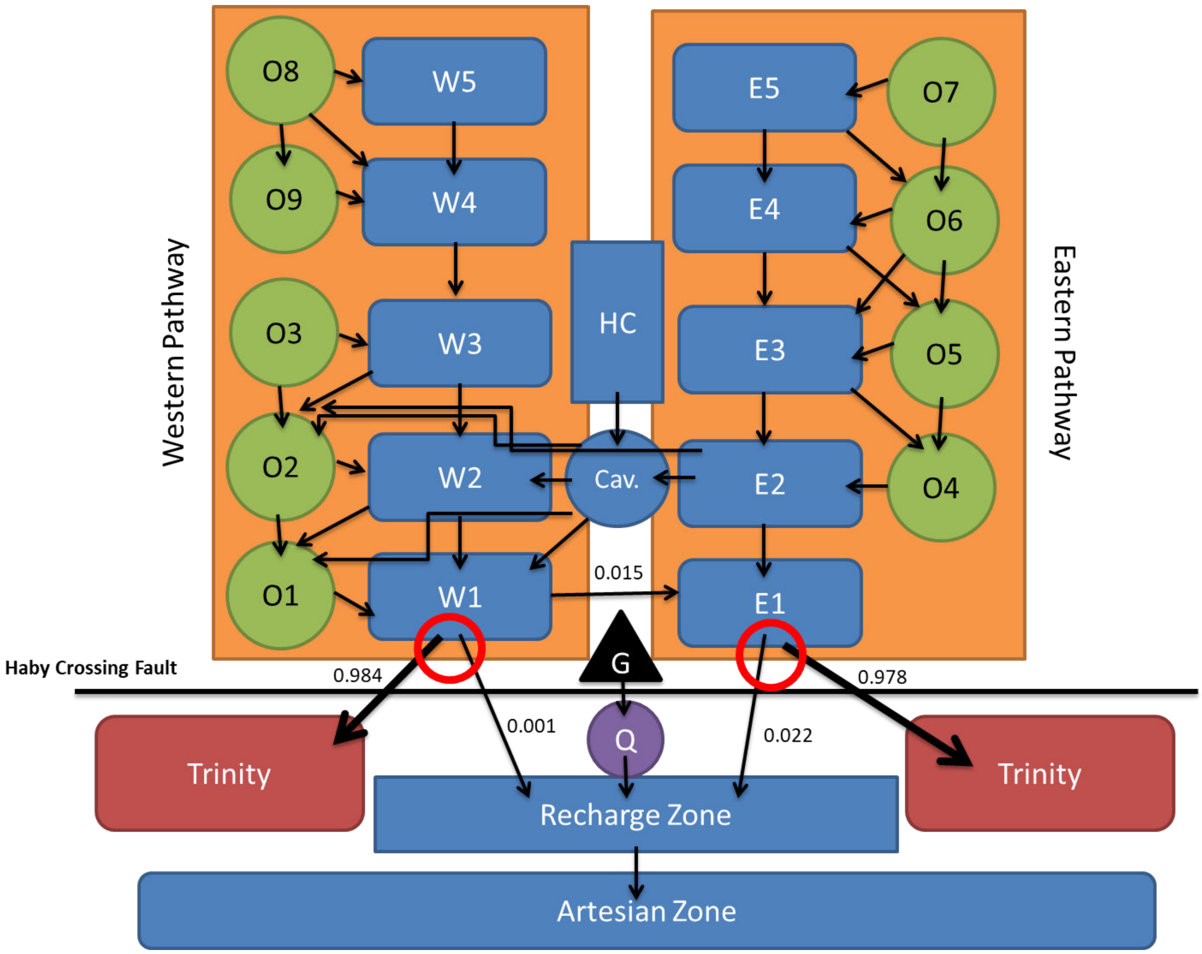


Figure 4-12 Infographic for sensitivity analyses changing the flow partitioned from W1 and E1 directly to the Edwards Aquifer recharge zone.

The red circles indicate location of modification; Flow is depicted within and from Western and Eastern pathways of the Helotes Creek watershed (noted by "W" and "E" elements) across Haby Crossing Fault (dark line) to the recharge zone; OSSF and TLAP reservoirs are noted by green circles, "HC" represents Helotes Creek, "Cav." represents the Cavernous stream valley, "G" represents the USGS gage, and "Q" represents the quarry; numbers on arrows from W1 and E1 indicate fractions of flow flowing to the different downstream reservoirs.

5 Results

5.1 MODPATH Particle Tracking Analysis

MODPATH particle tracking analysis was undertaken to determine the timing and extent of mass transport from different wastewater disposal facilities to the Edwards Aquifer based on the steady-state flow solution from the Helotes Creek watershed integrated hydrologic model. **Figure 5-1** shows the distribution of travel times for particles tracked forward from the water table beneath each of the twelve possible inflow polygons. As discussed elsewhere in this report, because travel times are contingent on the assumption that flow is through porous media, rather than a karstic carbonate aquifer with both conduit and diffuse flow, absolute travel times as uncertain, if not misleading. Relative differences in travel times among the Base Case and the eight scenarios, however, can be informative. **Figure 5-2** shows the results of reverse particle tracking for particles originating at the north face of the Edwards Receiving ZoneBudget Zone. It should be noted that travel-time results from particle tracking analyses are inversely proportional to the effective porosity values used for analysis. The effective porosity values used for this analysis were the same as the representative values used in the integrated hydrologic model, which is a further reason that travel-time results should not be interpreted as absolute values. Instead, travel-time values serve as a tool for comparison to determine the relative speed at which particles move through different flowpaths.

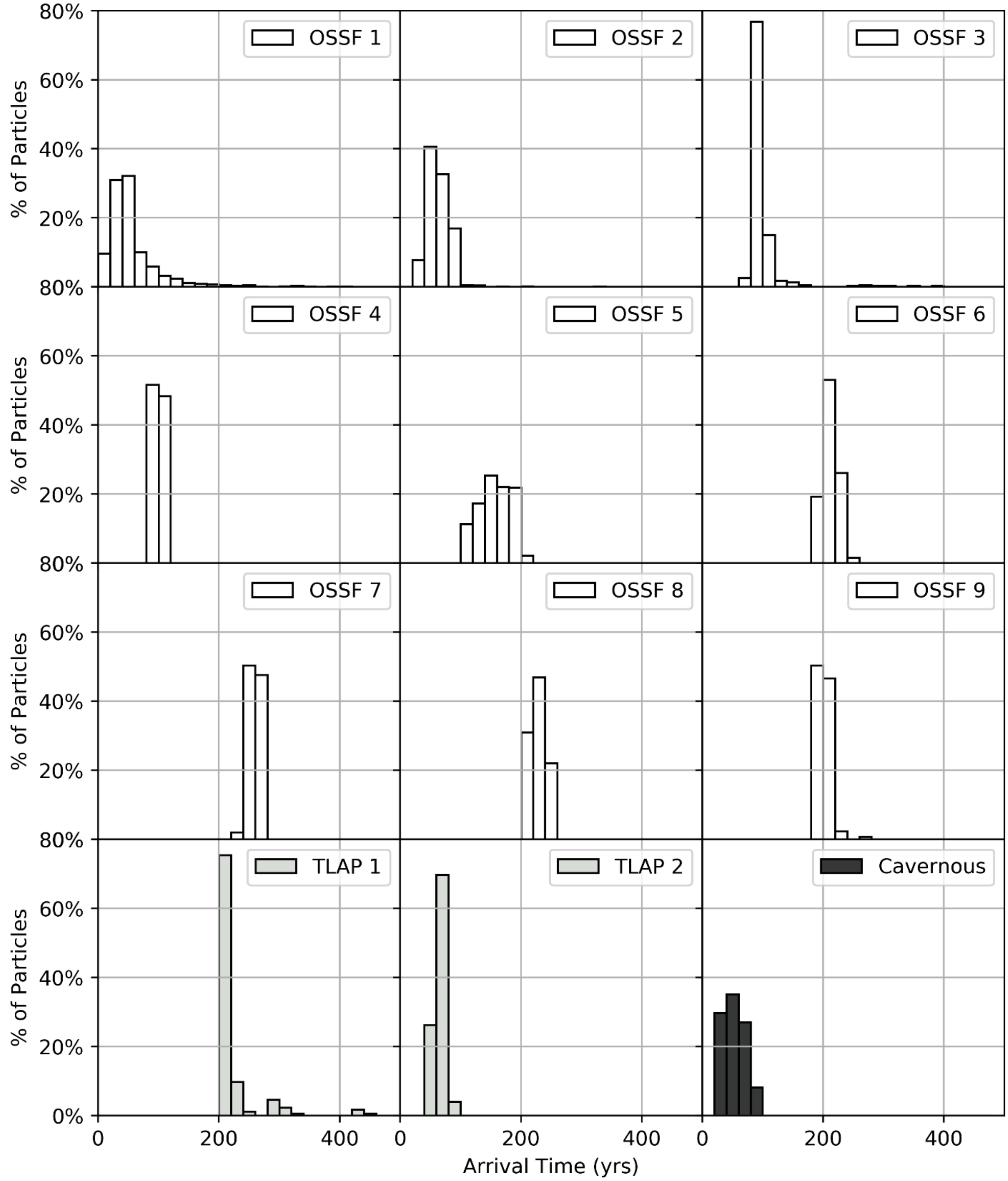


Figure 5-1 Histograms of particle arrival times (in years) at the Edwards Receiving ZoneBudget Zone for particles originating at the water table beneath each inflow polygon.

Particle travel times are based on forward particle tracking using MODPATH with flows from the steady-state solution for the Helotes Creek watershed integrated hydrologic model.

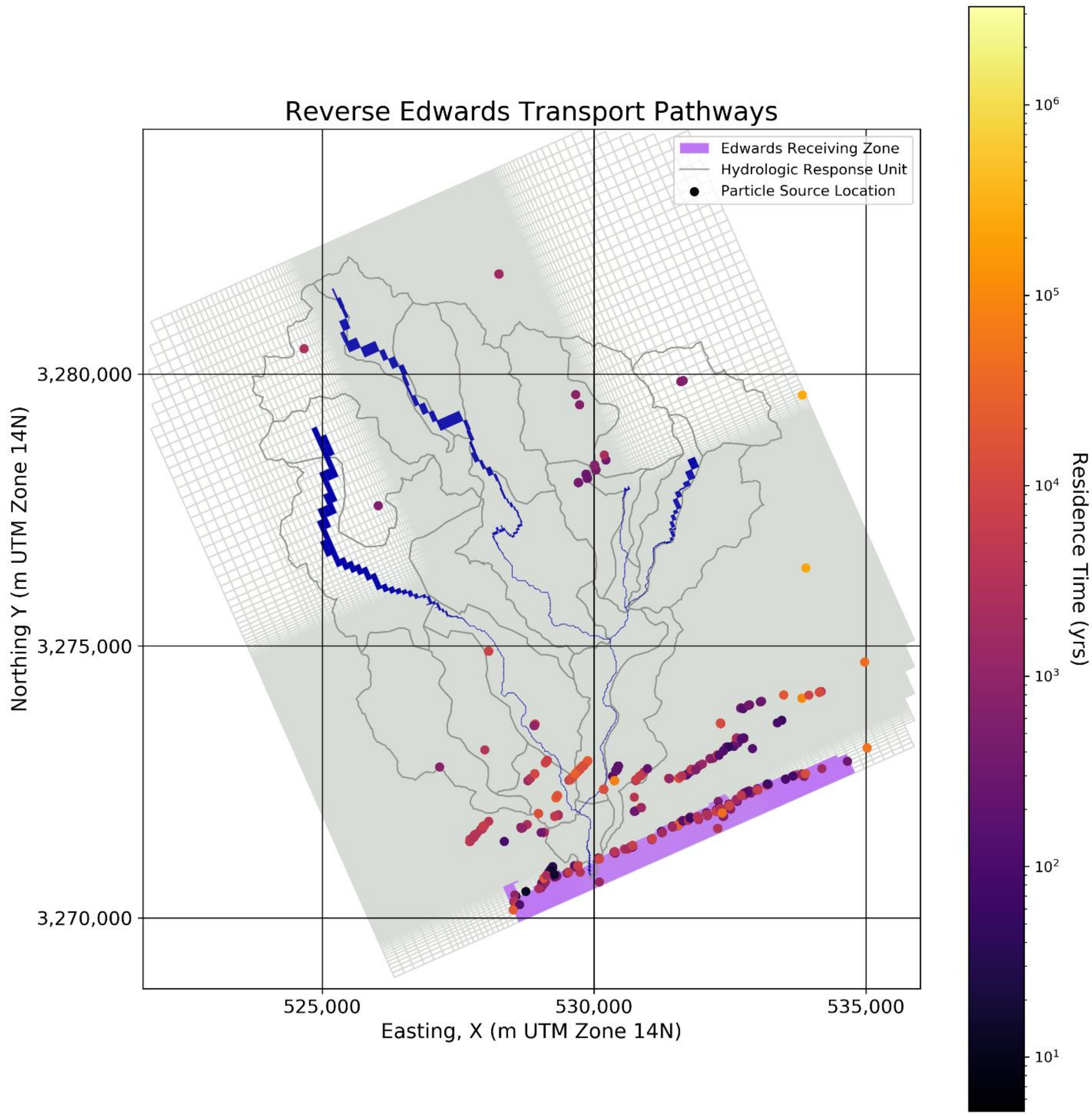


Figure 5-2 Endpoints from reverse particle tracking analysis.

Figure shows endpoints from the north face of the Edwards Receiving ZoneBudget Zone using MODPATH with flows from the steady state solution for the Helotes Creek watershed integrated hydrologic model. Each point represents the location where a particle terminated. Points are colored by residence time in the subsurface before reaching a termination point.

5.2 GoldSim Models

Solute-transport simulations carried out through GoldSim yield results regarding the quantity of mass transport in the watershed, as well as concentrations in conceptual reservoirs.Table 5-1 and **Table 5-2** showcase the total mass loading introduced as part of each simulation and the summary of cumulative volumes and masses into the Edwards Aquifer recharge zone, respectively.

Figure 5-3 and **Figure 5-4** illustrate comparisons between different wastewater disposal scenarios and their impact on mass transport to the Edwards Aquifer. It's important to note that, under the construct of this analysis and the manner in which flow receptors are defined, only about 1.15% of the flow and mass loading from Helotes Creek watershed is discharged directly to what is defined as the recharge zone outside of the Helotes Creek watershed study area. Conceptually, a significant portion of flow and mass loading from Helotes Creek watershed discharges first to the Trinity Aquifer, then to the Edwards Aquifer. **Figure 5-4** shows the cumulative mass to the Trinity Aquifer (and ultimately, the Edwards Aquifer) for each of the eight scenarios relative to cumulative mass for the Base Case.

Table 5-3, Figure 5-5 and **Figure 5-6** show the relative impact on the cumulative volumes and masses to the recharge zone of varying the effluent discharge from TLAP facilities in Scenarios 4 and 5. **Figure 5-7** shows the relative impact on cumulative mass to the recharge zone of increasing OSSF density for the Base Case and Scenarios 1 and 3. It includes Scenario 2 in a different color to make it possible to simultaneously compare the effect of increasing OSSF density with the effect of increasing the average mass loading at each OSSF.

Table 5-4 details the results of the sensitivity analyses used to test assumptions made about interformational flow from Helotes Creek during the conceptualization and parameterization of the model. **Figure 5-8** shows the impact on cumulative mass to the recharge zone relative to the Base Case of increasing the amount of flow going from the transport pathways to the recharge zone to 25%, 50%, 75% and 90% of the total flow exiting the transport pathways.

Table 5-1 Total mass loading for the Base Case and the eight scenarios.

A discharge of 680 per day per household, mass load concentration of 40 mg/L for all OSSFs except for the malfunctioning OSSFs in Scenario 2a which has a mass load concentration of 80 mg/L, and a mass load of 20 mg/L for all facilities are assumed.

Scenario	OSSFs	Flow/d L/d	Load/d kg/d	Facility MGD	Load/d kg/d	TOTAL kg/d
Base Case	1412	960,160	38.4	0	0	38.4
1	1627	1,106,360	44.3	0	0	44.3
2a	184	125,120	10.0	0	0	-
2b	1228	835,040	33.4	0	0	43.4
3	1516	1,030,880	41.2	0	0	41.2

4	1255	853,400	34.1	0.14	10.6	44.7
5	1080	734,400	29.4	0.05	3.8	33.2
6	1255	853,400	34.1	0.86	65.1	99.2
7	1080	734,400	29.4	0.34	25.7	55.1
8	1080	734,400	29.4	0.80	60.6	89.9

Table 5-2 Summary of cumulative volumes and masses to Edwards Aquifer recharge zone and the Trinity for Base Case and eight scenarios.

Simulation	Cumulative volumes to recharge zone (m³)	Cumulative masses to recharge zone (kg)
Base Case	502,600,000	1,294,000
1	502,600,000	1,513,000
2	503,400,000	1,462,000
3	502,600,000	1,447,000
4	502,600,000	1,357,000
5	502,600,000	1,272,000
6	502,600,000	1,587,000
7	502,600,000	1,378,000
8	467,600,000	1,527,000
	Cumulative volumes to Trinity (m³)	**Cumulative masses to Trinity (kg)**
Base Case	5.68E+10	1.34E+08
1	5.68E+10	1.54E+08
2	5.68E+10	1.51E+08
3	5.68E+10	1.44E+08
4	5.68E+10	1.81E+08
5	5.68E+10	1.18E+08
6	5.68E+10	3.54E+08
7	5.68E+10	1.97E+08
8	2.25E+10	3.09E+08

Table 5-3 Cumulative volumes and masses to recharge zone from alternative TLAP SADDS scenarios.

TLAP Scenario	Cumulative volumes to recharge zone (m³)	Cumulative masses to recharge zone (kg)
4 - 0.14 MGD	502,600,000	1,357,000
4 - 0.28 MGD	504,900,000	1,406,000
4 - 0.56 MGD	510,000,000	1,507,000
5 - 0.05 MGD	502,600,000	1,272,000
5 - 0.10 MGD	503,300,000	1,290,000
5 - 0.20 MGD	505,100,000	1,327,000

Table 5-4 Cumulative volumes and masses to recharge zone resulting from recharge zone sensitivity analyses 1 through 4.

Test	Cumulative volumes to recharge zone (m^3)	Cumulative masses to recharge zone (kg)
1	1.45E+10	3.41E+07
2	2.89E+10	6.82E+07
3	4.34E+10	1.02E+08
4	5.68E+10	1.34E+08

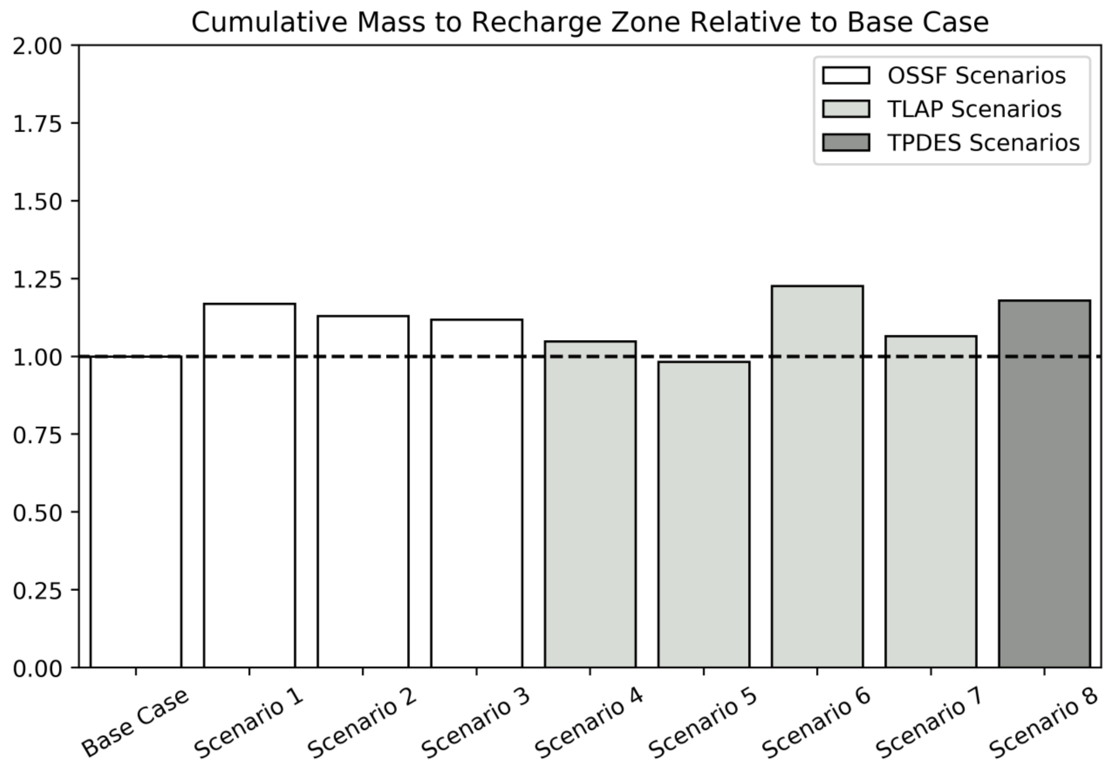


Figure 5-3. Comparisons between different wastewater disposal scenarios and their impact on mass transport to the Edwards Aquifer recharge zone

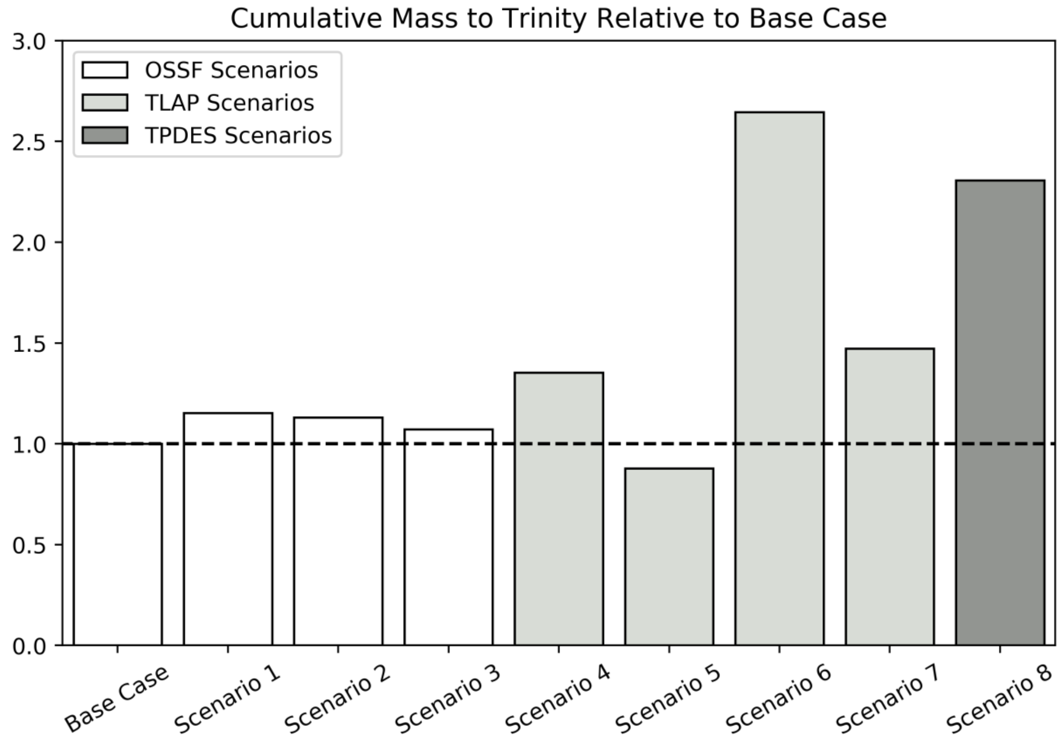


Figure 5-4. Comparisons between different wastewater disposal scenarios and their impact on mass transport to the Trinity Aquifer

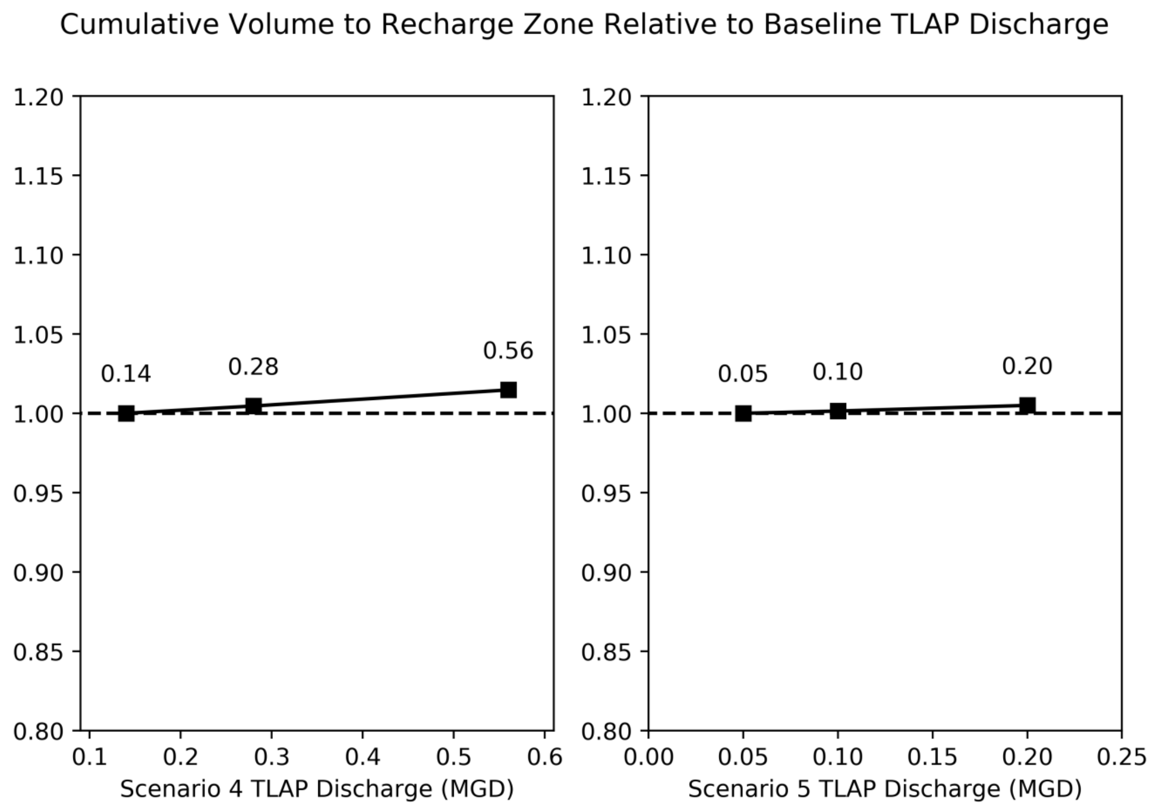


Figure 5-5. Relative impact on the cumulative volumes to the recharge zone of varying the effluent discharge from TLAP facilities in Scenarios 4 and 5

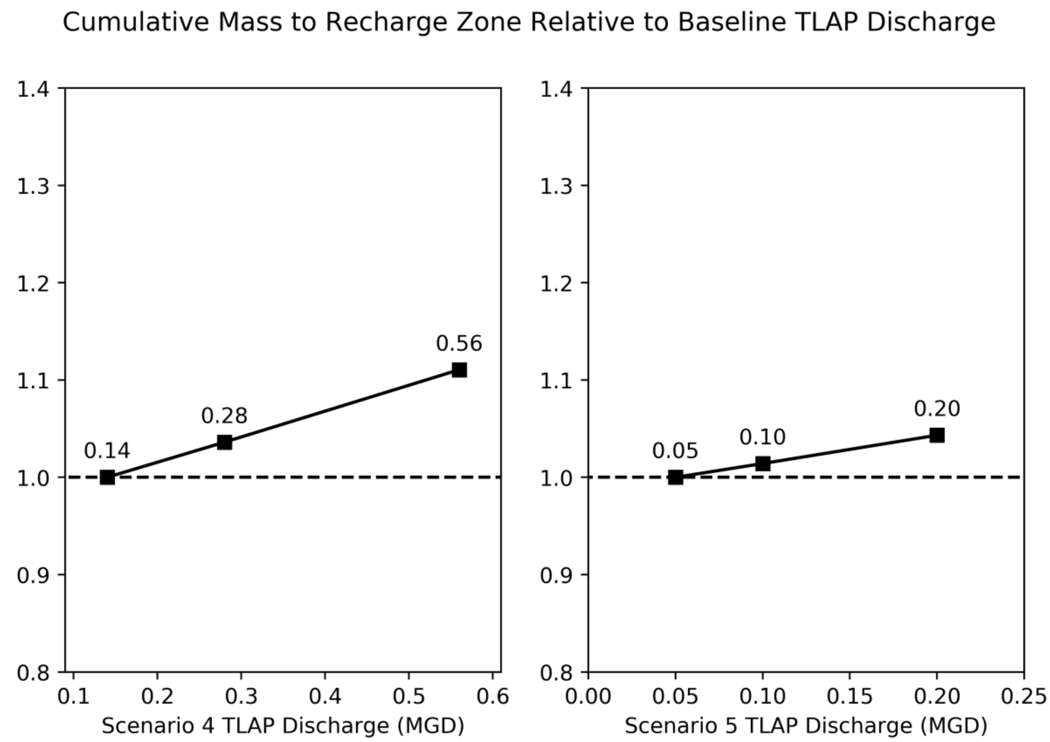


Figure 5-6. Relative impact on the cumulative masses to the recharge zone of varying the effluent discharge from TLAP facilities in Scenarios 4 and 5

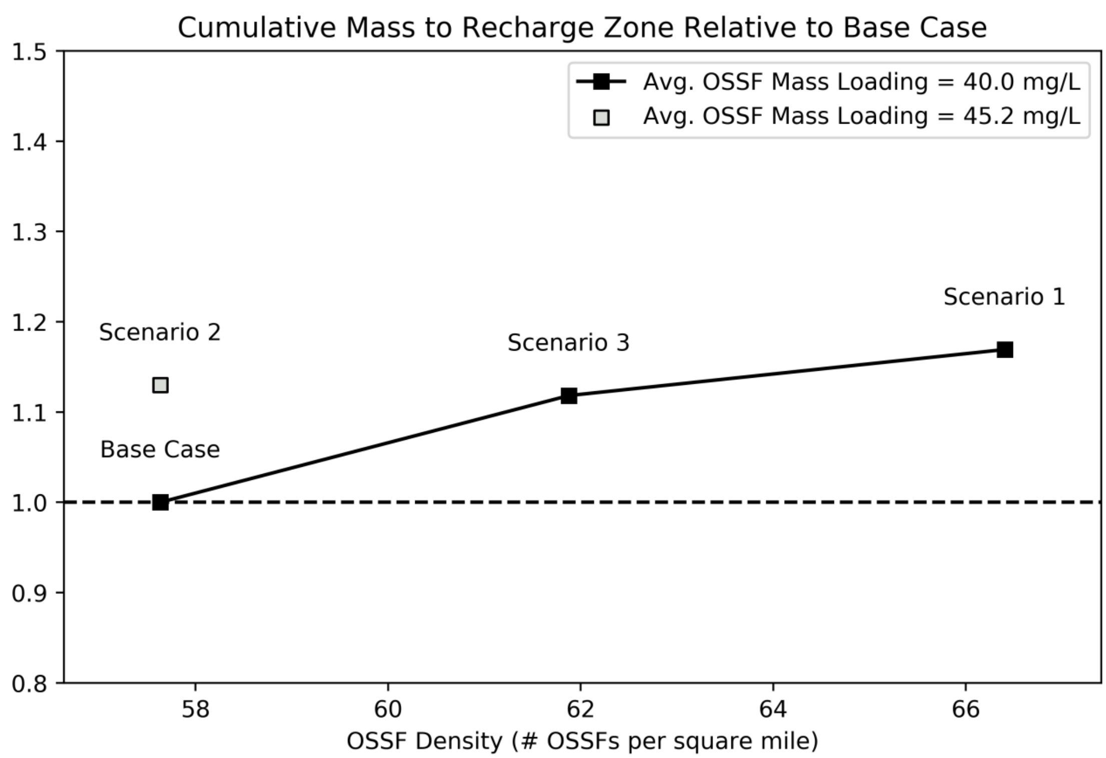


Figure 5-7. OSSF density among OSSF scenarios and comparative cumulative mass to recharge zone.

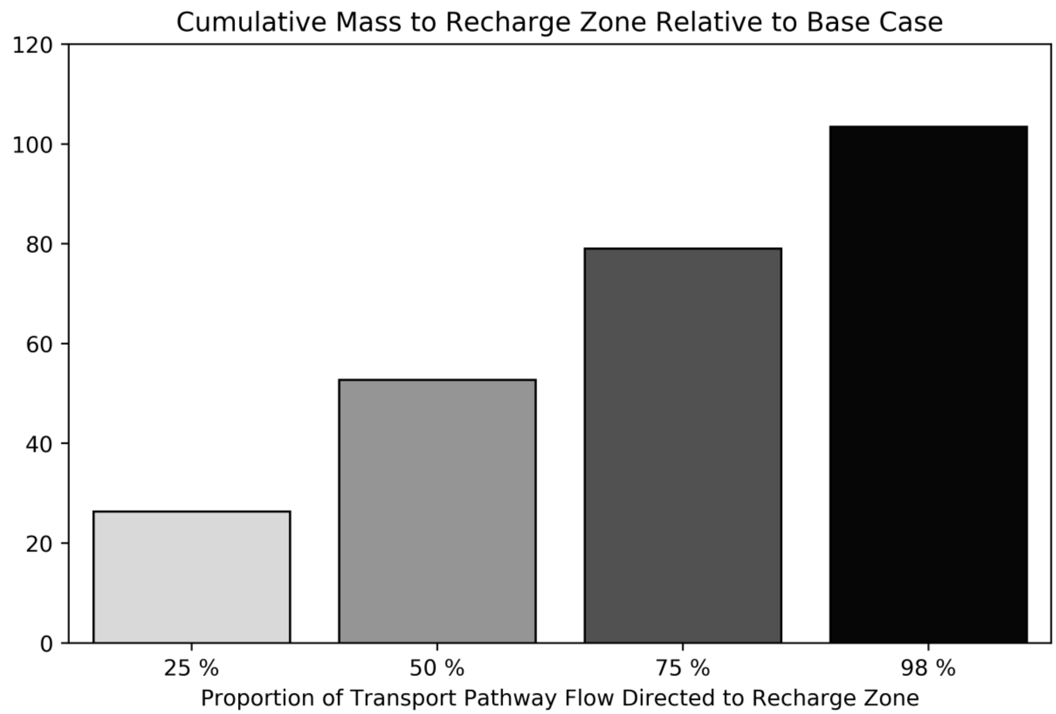


Figure 5-8. Depiction of recharge zone sensitivity analyses 1 through 4.

6 Discussion

The calibrated Helotes Creek watershed Integrated Hydrologic model yields reasonable estimates for regional groundwater-flow directions and rates. The model is a useful tool because it combines meteorological and terrain characteristics of the watershed, the geologic framework of the region, our conceptual hydrologic model – including general hydrostratigraphic characteristics of each geologic material, qualitative knowledge of gaining and losing reaches in Helotes Creek, and spatial knowledge of where interformational flow and direct recharge to the Edwards Aquifer recharge zone occur, –and a limited amount of calibration data. Model results indicate that it effectively simulates surface-water and groundwater flow in the Helotes Creek watershed. In this way, it effectively synthesizes all available information and is able to simulate the most essential hydrologic characteristics of the watershed as best we understand them.

The Helotes Creek watershed study area relies solely on OSSF-type wastewater disposal facilities. Neither TLAP- nor TPDES-type wastewater disposal facilities are present in the watershed. For this reason, eight hypothetical scenarios were identified to explore and evaluate the relative impact that different wastewater disposal facility type and the location of each facility within the Helotes Creek watershed would have on recharge to the Edwards Aquifer. A transport model that relied on flow fields generated by the integrated hydrologic model was used to simulate each the Base Case and the eight scenarios that represent the three wastewater disposal facility types under a variety of conditions. Given the absence of either a TLAP or TPDES in the Helotes Creek watershed, in particular, and the paucity of relevant data on discharge input and impacts, in general, data drawn from other geographic locations within the Texas Hill Country were used to develop the eight scenarios.

Results of the Base Case and eight scenario analyses (**Table 5-2**) indicate all scenarios, with the exception of Scenario 5 (TLAP SADDS in the southern portion of the watershed) would generate greater mass loadings discharged to the Edwards Aquifer relative to the status quo represented by the Base Case (**Figure 5-3** and **Figure 5-4**). There are marginal increases to the mass loading to the Edwards Aquifer for the three OSSF-based scenarios (i.e., Scenario 1 – accounting for non-permitted OSSFs; Scenario 2 – accounting for malfunctioning OSSFs; Scenario 3 – additional OSSFs associated with future residential construction in the northern portion of the watershed) as would be expected. Increases for these scenarios were no greater than about 15.3% relative to the Base Case.

As shown in **Figure 5-4**, higher OSSF density in the Helotes Creek watershed resulted in higher cumulative masses to the recharge zone. However, cases of lower density but higher effluent concentrations could result in higher cumulative mass to the recharge zone than cases of higher density but lower effluent concentrations, as highlighted by Scenario 3. Scenario 3, in which there is an increase in OSSFs in the northern OSSF groups, demonstrated the lowest cumulative mass to the recharge zone among the hypothetical OSSF scenarios. This indicates that, with respect to OSSFs, a greater distance from the recharge zone could result in lower impacts to the waters that recharge the Edwards Aquifer.

Scenarios 4 through 8 were conceived to assess the impact of non-OSSF wastewater disposal facilities on the Edwards Aquifer. The size of the TLAP and TPDES facilities were predicated on available land in Helotes Creek watershed, 32 acres at the location in the northern portion of the watershed, and 13 acres in the southern, more developed, portion of the watershed. Available land was the factor used to determine the capacity of the TLAP facilities.

The results from both the northern TLAP SADDS and TLAP SS scenarios resulted in higher cumulative mass to the recharge zone than their southern counterparts. This is likely due to the larger application area and increased commensurate effluent disposal of the northern TLAP scenarios. The application rate for a TLAP SS facility is 0.1 gal/ft^2/day, which comports with the maximum allowable application permitted in this region of Texas. The application rate for a TLAP SADDS facility is 0.060 gal/ft^2/day, which is within the range of application rates of similar facilities in other areas of the Texas Hill Country. Hence total discharge at the northern location was greater than the discharge rate at the southern location due to reduced acreage at the southern location.

Scenario 5, in which a TLAP SADDS facility in the southern portion of Helotes Creek watershed replaced the OSSFs that formed OSSF group 2 in the Base Case, had the lowest mass loading to the Edwards Aquifer that was equivalent to about 88% of the mass loading of the Base Case (**Figure 5-3** and **Figure 5-4**). The decrease in mass loading is attributed to the fact that removal of group 2 OSSFs has a greater impact than the inclusion of a TLAP SADDS facility in the southern portion of the watershed.

The four remaining scenarios exhibited sizable increases to mass loading discharged to the Edwards Aquifer. Installation of the two types of TLAP facilities (i.e., Scenario 4 – SADDS in the north and Scenario 7 – SS in the south) released approximately 1.35 and 1.47 times more mass loading to the Edwards Aquifer relative to the Base Case, respectively.

The sole scenario of a TPDES facility (Scenario 8) discharged approximately 2.3 times as much mass loading to the Edwards Aquifer relative to the Base Case. The TPDES was located in the southern portion since it is likely that a centralized wastewater facility would be located downgradient from residences that discharge wastewater to the facility.

Scenario 6, in which a TLAP SS facility is located in the northern portion of Helotes Creek watershed and replaces the OSSFs that formed part of OSSF groups 8 and 9 in the Base Case, had the highest mass loading to the Edwards Aquifer (**Figure 5-3** and **Figure 5-4**). Scenario 6 released approximately 2.63 times as much mass loading to the Edwards Aquifer relative to the Base Case.

Model simulation results indicate that the extent of impact from TLAP and TPDES facilities depends on location and method. For both TLAP SS and TLAP SADDS facilities, being located in the northern portion of the Helotes Creek watershed resulted in significantly greater mass loading to the Edwards Aquifer when compared with locations in the south. This result is likely a result of the higher level of mass loading at the northern location compared with the southern location due to larger available land for wastewater application (i.e., 32 acres at the northern location versus 13 acres at the southern location).

MODPATH particle tracking analysis was used to determine flowpaths for particles based on the steady-state solution for groundwater flow in the region. Forward particle tracking from locations at the water table directly below real and hypothetical wastewater disposal facilities, detailed in **Figure 4-3**, **Figure 4-4**, and **Figure 4-5**, indicates that solute transport occurs in the direction of the Edwards Aquifer recharge zone from all facilities. As shown in **Figure 5-1**, particles originating closer to the Edwards Aquifer recharge zone, i.e. in the southern portion of the watershed near the outlet, have shorter travel times than those in the upland, northern portions of the watershed. The existence of hypothesized pathways directly to the recharge zone for surface water in Helotes Creek via the quarry implies that near-stream locations in the contributing zone are more vulnerable to degradation for wastewater disposal methods where some portion of the mass loading runs off to streams, specifically TLAP aerial dispersal methods. Additionally, the relatively short travel time for particles that infiltrate into the Cavernous Glen Rose from Helotes Creek compared to particles that load to the water table elsewhere provide additional support for the fact that near-stream locations are vulnerable to degradation when some portion of the mass loading from a facility can enter the stream. Ultimately, flow from Helotes Creek watershed is to the Edwards Aquifer, whether as surface flow to the recharge zone in the quarry or as groundwater either directly from the Edwards Aquifer or via the Trinity Aquifer (**Figure 6-1**).

The number of households served by these facilities is calculated using the estimate that 680 L of wastewater is generated per day per household (**Table 3-2**). Acreage required for this number of households can be calculated by estimating how many homes per acre are built in the hypothetical development(s). **Table 6-1** assumes 3.5 households per acre although some developments have as many as six homes per acre. If more households are built per acre, total acreage for the development(s) would be less. Given that Helotes Creek watershed covers 15,560 acres with large undeveloped tracts, opportunities exist for construction of developments requiring 80 to 1,368 acreages.

Table 6-1 Wastewater rate disposed, equivalent homes, and required acres for scenarios 4 -7.

Equivalent home calculation is predicated on the assumption that each household generates 680 L effluent per day.

Scenario	L/d	Equivalent homes	Required acres
4	529,957.6	779	223
5	189,270.6	278	80
6	3,255,454.1	4,787	1,368
7	1,287,040.0	1,893	541
8	3,028,329.4	4,453	1,272

The trophic state of Helotes Creek is slightly mesotrophic or oligotrophic based on sampling of sestonic chlorophyll (Section 2.5.7). Benthic chlorophyll sampling indicates that the Helotes Creek watershed might be classified as oligotrophic or slightly mesotrophic. Replacement of OSSFs in the southern portion of the watershed with a TLAP SADDS with limited disposal capacity (i.e., 0.05 MGD) would not likely impact the trophic state of the watershed (Scenario 5). Installation of larger systems, such as the TLAP in Scenarios 4, 6, and 7 or the TPDES in Scenario 8, however, would add sufficient mass loading (i.e., nutrients) to the system to potentially alter the trophic state to be mesotrophic or eutrophic (Mabe, 2007; Herrington, 2010).

Sensitivity Analyses

The sensitivity analyses involving increased effluent discharge from TLAP SADDS facilities predictably demonstrated increased cumulative volumes and masses to the Edwards Aquifer recharge zone (**Table 5-3, Figure 5-5, and Figure 5-6**). The four tests in which both the volume and mass flows issuing from W1 and E1 were increasingly directed to the Edwards Aquifer recharge zone predictably demonstrated an increase in cumulative volumes and masses to the recharge zone (**Table 5-4** and **Figure 5-5**).

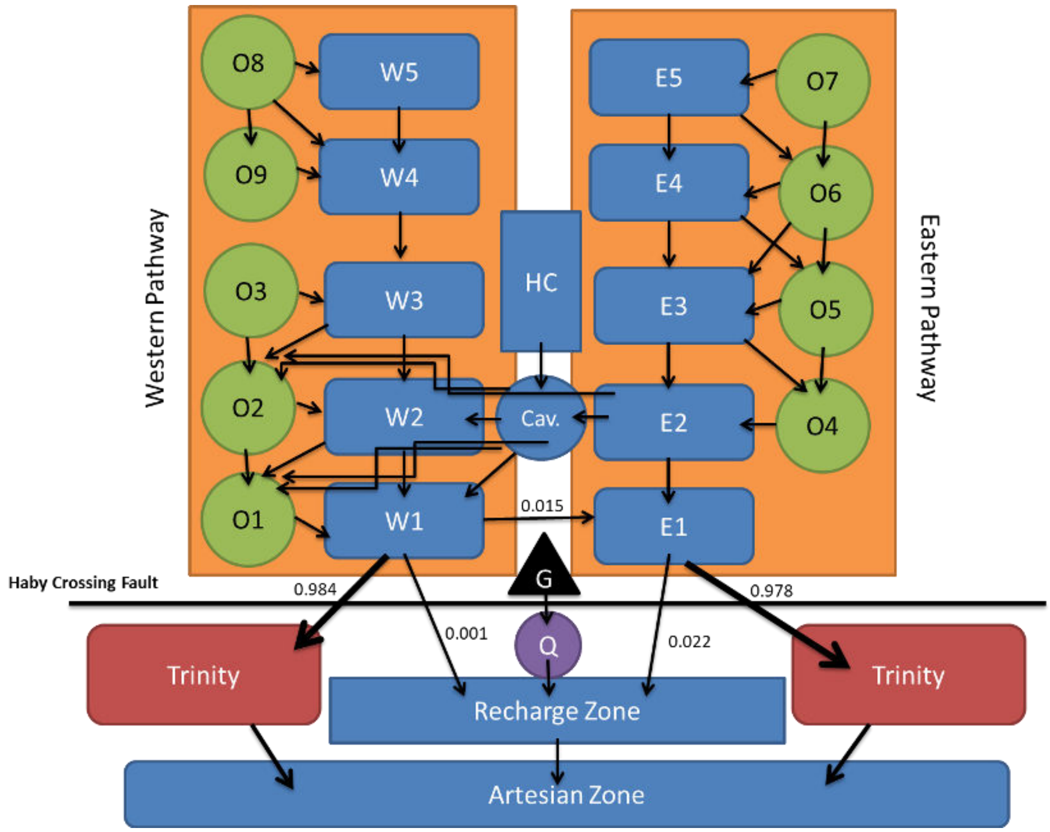


Figure 6-1. Infographic depicting the flow from the Helotes Creek watershed exiting via the Edwards Aquifer recharge zone and Trinity units to the Edwards Aquifer artesian zone

Figure depicts flow within and from Western and Eastern pathways of the Helotes Creek watershed (noted by "W" and "E" elements) across Haby Crossing Fault (dark line) to the recharge zone; OSSF and TLAP reservoirs are noted by green circles, "HC" represents Helotes Creek, "Cav." represents the Cavernous stream valley, "G" represents the USGS gage, and "Q" represents the quarry; numbers on arrows from W1 and E1 indicate fractions of flow flowing to the different downstream reservoirs.

7 Limitations

Groundwater flow in both the integrated hydrologic model and the transport model is characterized as porous media flow, even though both the Edwards and Trinity aquifers are clearly recognized as karstic carbonate aquifers which exhibit both conduit and media flow (Green et al., 2014; Sharp et al., 2019). Although groundwater flow patterns could change slightly if characterized and modeled as a conduit/diffuse flow system rather than a porous media flow system, the most prominent difference between the two flow characterizations is flow and transport velocity. For this reason, flow and transport velocity simulations are not recognized as realistic or meaningful. This limitation is not overly onerous when evaluating the simulation outputs because the objective of the study was to compare flow and transport for different wastewater disposal facilities in which all scenarios are predicated on identical flow mechanisms. Hence, relative differences in flow and transport attributes among the scenarios are the key output, not absolute flow and transport velocities.

The lack of water-level data for most formations included in the model, quantitative constraints on surface-water/groundwater interactions in Helotes Creek, and quantitative constraints on interformational flow at Haby Crossing Fault limit the extent to which the model can be calibrated to represent real-world flows. The transport model estimated transport rates and mass for different reservoirs predicated on flows simulated with the integrated hydrologic model. Results from the transport model are sufficiently accurate to compare the relative mass loadings generated by different wastewater disposal facilities, but are not sufficiently constrained to ascertain actual flow paths and rates.

One unanswered question is whether wastewater disposal facilities that load mass to the stream rather than to the water table have a relatively larger impact. Simulated impacts on cumulative mass for the hypothetical TLAP SS and TPDES facilities in Scenarios 6-8 (**Figure 5-3** and **Figure 5-4**) provide insight. The two simulated largest mass loadings are the northern TLAP SS (Scenario 6) and the TPDES located in the south (Scenario 8). Differentiating differences between their relative impacts exceeds the resolution of the simulations. Additional combined field and possibly laboratory studies are needed to provide the bases to resolve this question. In particular, the ability of soils present in Helotes Creek watershed to impede infiltration of the solute to the water table or to affect overland flow would benefit the determination of this question. In addition, the model assembled for flow and transport analysis in this study lacks sufficient resolution to discern the second-order differences in transport in the two scenarios. Regardless, the model assembly was effective in demonstrating the relative greater mass loading experienced in the northern TLAP SS and the TPDES located in the southern portion of Helotes Creek watershed.

8 Conclusion

An integrated hydrologic model of Helotes Creek watershed was developed to generate surface-water/groundwater regimes of the study area. A transport model calculated transport rates and mass inflows for different reservoirs predicated on flows simulated with the integrated hydrologic model. The integrated hydrologic model developed for Helotes Creek watershed incorporated all available information and data for the study site. Nonetheless, during development of the model, it became apparent that this information and data were insufficient to develop a robust comprehensive model of the study domain. Although this shortcoming limits the model when attempting to make detailed, high-resolution predictions of flow and transport in the Helotes Creek watershed, the model is shown to be useful and defensible when making comparative assessments in which the foundational conceptualizations are the same for the cases being compared.

A Base Case model was constructed to replicate, to the degree possible, mass loading from OSSFs currently present in Helotes Creek watershed. Mass loading for the Base Case was calculated using the transport model predicated on flows generated using the integrated hydrologic model. Mass loadings from eight alternative scenarios generated by different wastewater disposal facilities were calculated using the same modeling assembly. Mass loadings calculated for the eight scenarios were compared with the Base Case to provide insight on the relative impact that different wastewater disposal facilities would have on the quality of water recharged to the Edwards Aquifer.

The scenarios were developed to evaluate the anticipated impact on recharge to the Edwards Aquifer from a variety of OSSF scenarios and from hypothetical TLAP and TPDES wastewater facilities in Helotes Creek watershed. For TLAP and TPDES scenarios, OSSFs in the model were removed from the area proximal to the hypothetical wastewater disposal facility to remove duplication of wastewater disposal.

Two locations in the watershed were considered for TLAP facilities, one in the less developed upgradient northern portion of the watershed and one in the more developed southern portion. Mass loading from each system was predicated on the size of the land available at each site, 32 acres at the northern location and 13 acres at the southern location. Only one TPDES scenario was considered. It was located at the same site as the southern TLAP scenarios.

Volumetric wastewater volumes varied from 0.05 to 0.86 million gallons per day (MGD) in the various scenarios. Similarly, nitrogen loadings varied from 33.2 to 99.2 kg/d. Mass loading disposal at the northern location was greater than loading at the southern location, hence mass loading to recharge of the Edwards Aquifer was greater for scenarios that represented facilities at the northern location. The size and capacity of the hypothesized wastewater facilities were reasonable and consistent with possible residential development in the study area. Capacity of the facilities was sufficient for upwards of 4,800 homes covering almost 1,800 acres. Residential developments of this size are conceivable within the 15,640 acres of the Helotes Creek watershed.

Modeling of the Base Case and eight scenarios demonstrates that the relative impacts of OSSFs, TLAP SADDS, TLAP SS, and TPDES practices vary depending on disposal type, mass loading, and location of the facilities. The simulation analyses illustrated that all scenarios resulted in higher cumulative mass to the recharge zone relative to the Base Case with the exception of the modest-sized TLAP SADDS, indicating that in cases of increased development or failure of OSSF systems, increased impacts to the quality of recharge to the Edwards Aquifer are to be expected. The scenarios with greatest impact on cumulative mass to the recharge zone were the large, northern TLAP SS scenario and the TPDES scenario. Differences in facility type may impact the delivery and whether any mass is diverted *en route* from the point of disposal to entry into the Edwards Aquifer, however, the bottom line is that greater discharge to the environment will result in greater mass loading to recharge of the Edwards Aquifer.

Water chemistry analyses of nutrients were inconclusive with respect to characterizing the Helotes Creek watershed's trophic state. However, periphyton and sestonic sampling and analysis indicate that the current trophic state of the Helotes Creek watershed is oligotrophic and possibly slightly mesotrophic which suggests that the stream and stream system have been marginally impacted by wastewater discharges, although more comprehensive sampling would be required to refine this characterization. Currently, OSSFs are the only type of wastewater disposal facility used in the Helotes Creek watershed. Transport simulations support the argument that if either a TLAP or TPDES facility were to be installed in Helotes Creek watershed and that the cumulative amount of wastewater disposed was substantially increased, the trophic state of Helotes Creek would be further degraded and likely classified as fully eutrophic.

9 Recommendations

As described herein, an integrated hydrologic model of Helotes Creek watershed was developed to generate surface-water/groundwater regimes of the study area. A transport model estimated mass flows for different reservoirs predicated on flows simulated with the integrated hydrologic model. A Base Case model was constructed to replicate, to the degree possible, mass loading from OSSFs currently present in Helotes Creek watershed. Mass loading for the Base Case was calculated using the transport model predicated on flows generated using the integrated hydrologic model. Mass loadings from eight alternative scenarios generated by different wastewater disposal facilities were calculated using the same modeling assembly. Mass loadings calculated for the eight scenarios were compared with the Base Case to provide insight on the relative impact that different wastewater disposal facilities would have on the quality of water recharged to the Edwards Aquifer.

Although eight scenarios were considered in the current project, evaluation of additional scenarios could provide further insight into the impact of other possible wastewater disposal facility types, locations, or number of units. Calculation of mass loadings for additional scenarios would not be a large effort if flow conditions remain the same as was assumed for the eight scenarios already considered. Additional scenarios could address the following hypothetical cases:

- Replacing all existing OSSFs with a centralized wastewater disposal facility.
- Higher density residential construction that would warrant additional or larger wastewater disposal facilities.
- Placement of wastewater facilities at alternative locations within Helotes Creek watershed.
- Revise loadings for the TLAP facilities by increasing or decreasing the size of land used for land application.
- Explore the impact of OSSF density and location by altering actual OSSF locations with hypothetical OSSF locations.
- Modify the distance of TLAP and TPDES facilities from creek channels, in both the northern and southern portions of the Helotes Creek watershed.
- Compare TLAP and TPDES facilities with similar capacity placed at different locations within the watershed.

These recommendations fall within the constraint of the current EAPP project, namely that the project be fully contained within the boundaries of Bexar County. Now that a transport/flow model structure is developed and available, it would be informative to apply the model to critical areas in the Edwards Aquifer contributing and recharge zones located outside of Bexar County. The Concan recreational area in northern Uvalde County is an example of a rural area whose natural resources are under significant pressure due to expanded recreational and residential development. The debate regarding this development includes the critical question regarding which types of wastewater disposal facilities would have greater (or lesser) impact on the quality of the river and associated river systems.

There are clearly other areas in the Edwards Aquifer contributing and recharge zones experiencing similar development pressures. Having the ability to quantitatively calculate the impact in terms of mass loading on rivers and streams would greatly enhance the ability of the: 1) City of San Antonio to measure the impact from protecting lands as part of the EAPP; and 2) Texas Commission on Environmental Quality to evaluate the impact of the installation of wastewater disposal into rivers and streams in the Edwards Aquifer contributing and recharge zones as part of its permitting processes.

Extension of the modeling technology developed by this project to other applications would be more extensive than simply using the Helotes Creek watershed model to evaluate additional scenarios. Namely, an integrated hydrologic model would need to be developed for each watershed targeted for evaluation. The workflow to develop the integrated hydrologic model has been developed as part of this project and is now available, however, data for each location would need to be compiled, a hydrostratigraphic model would need to be constructed, and model synthesis and calibration would be necessary to generate the flow regimes appropriate for each watershed. Only then would solute-transport scenario testing be available to compare different wastewater disposal facility strategies for these additional watersheds.

Flow and transport were modeled based on the assumption that the Edwards and Trinity aquifers can be represented as porous media. Both aquifers, however, are karstic carbonate systems in which flow is appropriately defined as a conduit/diffuse flow system (Sharp et al., 2019). More representative flow and transport simulations would be generated if the models were converted to a conduit/diffuse flow system rather than porous media. This is not a trivial exercise and considerably more characterization data, including tracer testing, would be required before such a conversion could be undertaken (Scanlon et al., 2003; Green et al.,2006; Green et al., 2019a, 2019b).

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