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Assessment of Recharge Areas for Groundwater-Dominant Streams Inhabited by the Threatened Okaloosa Darter

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Abstract

Groundwater upwelling to creeks inhabited by the threatened Okaloosa darter (*Etheostoma okaloosae*) at Eglin AFB in northwestern Florida entered the sand and gravel aquifer as recharge in surrounding upland areas up to decades ago. Groundwater samples collected from below eleven headwater and eleven downgradient sites across six creek basins in February and December 2020 were analyzed in the field for temperature, specific conductance, pH, and dissolved oxygen, and in the laboratory for concentrations of sulfur hexafluoride (SF_6), dissolved gases (methane, carbon dioxide, nitrogen, oxygen, and argon), and the stable isotopes of hydrogen and oxygen of water. The SF_6-based ages of groundwater below the eleven headwater sites indicated recharge occurred between 2009 and 1992, or 11 to 28 years ago, respectively. Groundwater ages below downgradient parts of the same creeks indicated recharge occurred between 2015 and 1995, or 5 to 25 years ago. Headwaters in more natural areas had

older groundwater and, in contrast, headwaters in more urban areas had younger groundwater. When combined with representative values of hydraulic conductivity for the sand and gravel aquifer, the ages reveal that the extent of maximum recharge distance from the sampling sites ranged from 730 to 6,600 feet from the creeks. In general, the recharge distance was farther from the creek in the headwater sites in more natural areas compared to sites located downstream. The potential recharge zone was also more extensive (greater area) for all headwater sites and, in contrast, more restricted along narrow groundwater-flow pathways for all downstream sites, regardless of natural or urban land use. Darter populations may be preferentially protected from threats such as hazardous materials spills in those parts of the creeks characterized by older groundwater that recharged farther from the creeks, because natural attenuation processes in the aquifer (adsorption, dilution, and biodegradation) would act to decrease contaminants prior to discharge. In contrast, darter populations would be more vulnerable to such contamination or other land-use changes in creek segments characterized by younger groundwater that recharged closer to the creeks. This new information can be used by natural resource managers as additional evidence to support the USFWS Recovery Plan and proposed delisting of the Okaloosa darter from the Endangered Species List. Moreover, these results may also be enlightening to fisheries biologists who may be unaccustomed in considering the importance of groundwater inputs as related to fisheries management.

Introduction

The Okaloosa darter (*Etheostoma okaloosae*) is a small (< 1.93 inches (in.)), perch-like, benthic fish (figure 1) that inhabit only six small (3 to 30-feet (ft) wide), shallow, clear, creek systems that flow almost entirely within Eglin Air Force Base (AFB) and empty into three bayous of Choctawhatchee Bay in Walton and Okaloosa Counties in the panhandle of northwest Florida (figure 2). In 1973 the species was listed as Endangered by the U.S. Fish and Wildlife Service (USFWS) due to smothering of creek habitat by erosion during road and dam construction. Since then, much progress has been made to understand the biology and life history of the Okaloosa darters on Eglin AFB (Austin and others, 2011; Holt, Jelks, and Jordan, 2013). This information was used successfully to protect existing habitats and to restore imperiled habitats through correction of erosion, contouring roadways, and planting vegetation in upland areas (Reeves, Tate, Jelks, and Jordan, 2016). Success was facilitated by the fact that most of the drainage basins of the six creeks are managed by the Jackson Guard Natural Resources Division of Eglin AFB. As a result, in 2011 the Okaloosa darter was downlisted from Endangered to Threatened (Jelks, Tate, and Jordon, 2011).

Figure 1. An Okaloosa darter resting on the bottom of a creek whose sediment comprises white sand that is characteristic of the region’s sand and gravel aquifer (Photograph by Bill Tate, USFWS).

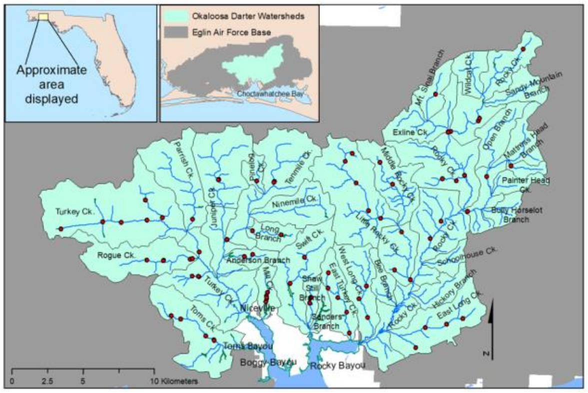


Figure 2. The creek basins that contain Okaloosa darters at Eglin AFB, northwestern Florida. Red circles are fixed sampling locations used by the USFWS to monitor darter populations over time. Surface-water boundaries related to land surface altitude are shown as black lines. Drainage on the western part of Eglin AFB is characterized by an east-west trellis pattern caused by unique headwater sapping. In contrast, drainage on the eastern part is a north-south dendritic pattern often seen in well-drained landscapes.

Any decision to completely remove the Okaloosa darter from the endangered species list, called delisting, necessarily would require data to meet Recovery Objectives. The USFWS defines "Recovery" as the reversal or arrest of a decline of an endangered or threatened species. The Recovery Objectives for the darter are to ensure that natural, historical flow regimes are maintained, and stream habitat, water quality, and water quantity are protected (U.S. Fish and Wildlife Service, 1998). Much has been done to restore natural surface-water flows, such as removal of obstacles that inhibit the in-stream passage of darters, and restoration of run-of-river flows. In contrast, even though groundwater has been recognized as the primary source of flow in the darter creeks (U.S. Fish and Wildlife Service, 1998), little data has been published on the impact of groundwater from the sand and gravel aquifer in providing groundwater discharge to the darter creeks. As such, delineation of the extent of recharge would provide new data that could be crucial in continuing the long-term management of Okaloosa darters, as well as other threatened species like the reticulated flatwoods salamander (*Ambystoma bishopi*). Elucidation of recharge to the creeks would help answer questions such as: "is there a difference in residence time (flow time) for flow in headwater locations compared to sites located farther downstream?" "how much time would be needed to remove any land-applied contaminants before they would arrive at the creeks, or the potential for the contamination to be attenuated prior to discharge?" Moreover, that such data be collected is imperative if future population increases or industrial growth is supported by new groundwater withdrawals from the sand and gravel aquifer.

Study Area

The creeks inhabited by the Okaloosa darter are in the western part of the extensive Choctawhatchee River and Bay watershed and drain into three Choctawhatchee Bay bayous (estuarine embayments) in Walton and Okaloosa Counties in the panhandle of northwest Florida near the city of Niceville (figure 2). The creeks flow almost entirely within Eglin AFB, one of the world's largest conventional weapons testing facilities.

Climate

The climate is generally humid and subtropical with warm summers and mild winters. The average summer temperature is 81 degrees Fahrenheit (°F), and the average winter temperature is 54 °F. At Niceville, FL, annual average precipitation from 1931 to 1978 was 62 inches (in.) (U.S. Department of Commerce, 1931-1978).

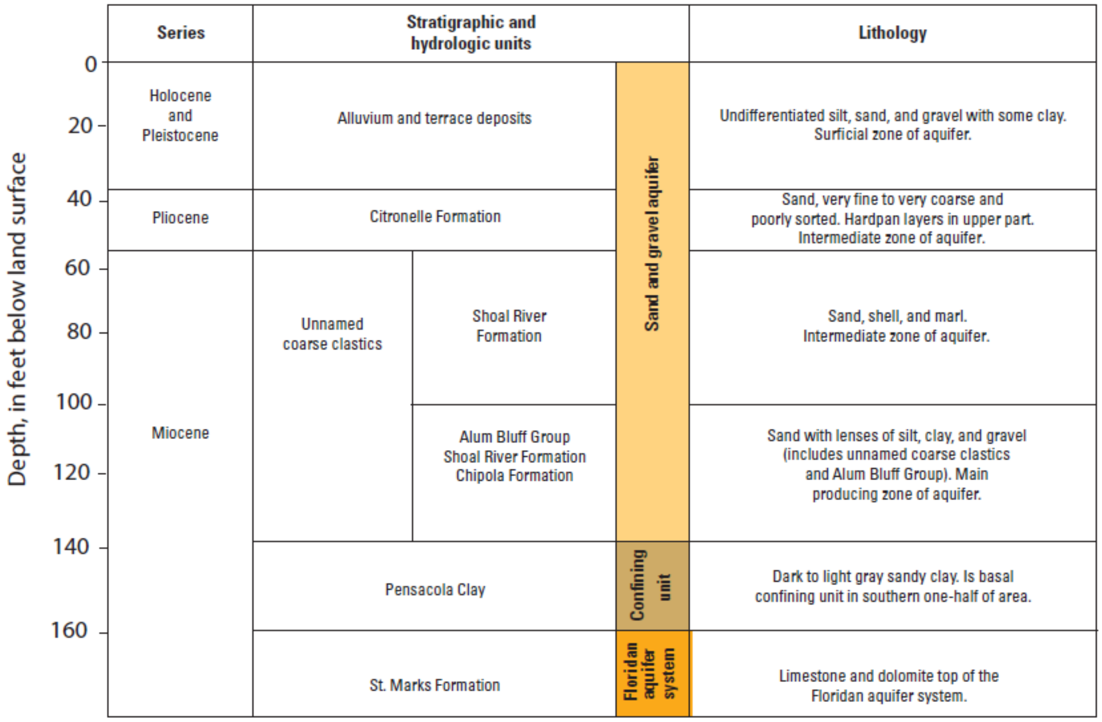
Physiography

The study area is in the Gulf Coastal Plain physiographic province. The area is characterized by a transition from deeper limestones that dominant the Floridan peninsula that are overlain by the quartz-rich unconsolidated sediments weathered from inland granitic rocks of the southern part of the Appalachian Mountains. The resultant regionally ubiquitous sandhills are dominated by deep-rooted longleaf pines (*Pinus palustris*) and wiregrass (*Aristida stricta*) and interspersed with small turkey oaks (*Quercus laevis*).

Topographic relief of the sandhills is greater than expected for most of Florida and is driven by erosion of these sandhills caused by both surface-water and groundwater. Drainage on the western part of Eglin AFB is characterized by an east-west trellis pattern (figure 2). This unique pattern was most likely created by headward erosion by groundwater sapping (Schumm and others, 1995) and has been seen at other high altitude, well drained coastal plain sediments (Landmeyer and Wellborn, 2013). Erosion of unconsolidated sands by sapping requires the downward flow of groundwater to be impeded by finer sediments such that the groundwater discharges at the land surface expression of the geologic contact. In contrast, drainage on the eastern part is a classic north-south dendritic pattern and has headwaters farthest inland. The latter drainage pattern is what is expected in a terrain dominated by well drained unconsolidated sand.

Hydrogeology

In general, the study area is underlain to depths of 250 ft below land surface (bls) by unnamed clastics (sands, silts, clays, and gravels) of Miocene age, the Pliocene Citronelle Formation, and undifferentiated alluvium and terrace deposits of Holocene to Pleistocene age (Marsh, 1966; figure. 3). These unconsolidated sediments record sedimentation by a prograding bayhead delta facies complex that lies unconformably over the Pensacola Clay of Miocene age. The Pensacola Clay was described by Hayes and Barr (1983) as a regional confining unit with low permeability. The Pensacola clay overlies differentiated and undifferentiated limestones of Early- to Middle-Miocene age that compose the deeper Floridan aquifer system. Most wells that pump water for human consumption tap the Upper Floridan.



Series	Stratigraphic and hydrologic units			Lithology
Holocene and Pleistocene	Alluvium and terrace deposits		Sand and gravel aquifer	Undifferentiated silt, sand, and gravel with some clay. Surficial zone of aquifer.
Pliocene	Citronelle Formation			Sand, very fine to very coarse and poorly sorted. Hardpan layers in upper part. Intermediate zone of aquifer.
Miocene	Unnamed coarse clastics	Shoal River Formation		Sand, shell, and marl. Intermediate zone of aquifer.
		Alum Bluff Group Shoal River Formation Chipola Formation		Sand with lenses of silt, clay, and gravel (includes unnamed coarse clastics and Alum Bluff Group). Main producing zone of aquifer.
	Pensacola Clay		Confining unit	Dark to light gray sandy clay. Is basal confining unit in southern one-half of area.
	St. Marks Formation		Floridan aquifer system	Limestone and dolomite top of the Floridan aquifer system.

Figure 3. Generalized stratigraphic column, Fort Walton Beach, near the study area at Eglin Air Force Base, Niceville, Florida (modified from Hayes and Barr, 1983). The six creek basins that are the focus of this current (2021) study cut down through the Holocene and Pleistocene sediments by groundwater from the surficial zone of the sand and gravel aquifer.

Specifically of relevance to the study, the sand and gravel aquifer covers all the land surface in the study area and comprises unconsolidated Holocene and Pleistocene alluvium and terrace deposits, the Citronelle Formation, and unnamed clastics of upper Miocene age (figure 3). In general, the sand and gravel aquifer comprise three zones based on differences in lithology and hydraulic properties: the surficial (water table, 0-60 ft bls), intermediate (lower permeability, 60-

125 ft bls), and main-producing (125-210ft bls) zones. The aquifer can reach a thickness up to 201 ft bls in southwestern Okaloosa County (Hayes and Barr, 1983). Moreover, the creeks studied in this effort have eroded through the Holocene and Pleistocene sediments and are fed groundwater from the surficial zone of the sand and gravel aquifer.

Creek flow

Groundwater from the sand and gravel aquifer has long been recognized as the primary source of water that flows in the darter creeks (U.S. Fish and Wildlife Service, 1998). This scenario of a shallow source of groundwater that supports surface-water flow stands in contrast with the more widely known scenario of the larger springs of Florida, which have as their source of flow groundwater from much deeper limestones of Miocene or older age.

The six creeks that are the focus of this study include Toms, Turkey, Mill, Swift, Deer Moss (formerly called East Turkey), and Rocky Creeks (figure 2). Total drainage of the six creeks is 176 square miles (m^2) (457-square kilometers [km^2]). Because the creeks are dependent on groundwater from the surficial zone of the sand and gravel aquifer rather than runoff, the creeks have an historically consistent discharge. For example, the median daily discharge, in cubic feet per second (cfs), on any given day is a consistent 89 cfs, based on 34 years of record (USGS Site ID 02367310, Juniper Creek at State Hwy 85 near Niceville) (figure 4). The consistent median daily discharge also suggests that (1) impacts from groundwater withdrawals from the sand and gravel or Upper Floridan aquifer have not affected creek flow, and (2) that climate changes are currently decoupled from stream flow. Short-term, transient, and rapidly dissipated peaks in discharge are due to direct addition of seasonal-driven, higher amounts of precipitation. Even though the summer months are characterized by higher amounts of precipitation (e.g., July is often characterized by 8 in. of precipitation), discharge is often at its lowest because the infiltrated groundwater is rapidly removed by evaporation and transpiration before the groundwater reaches the creeks.

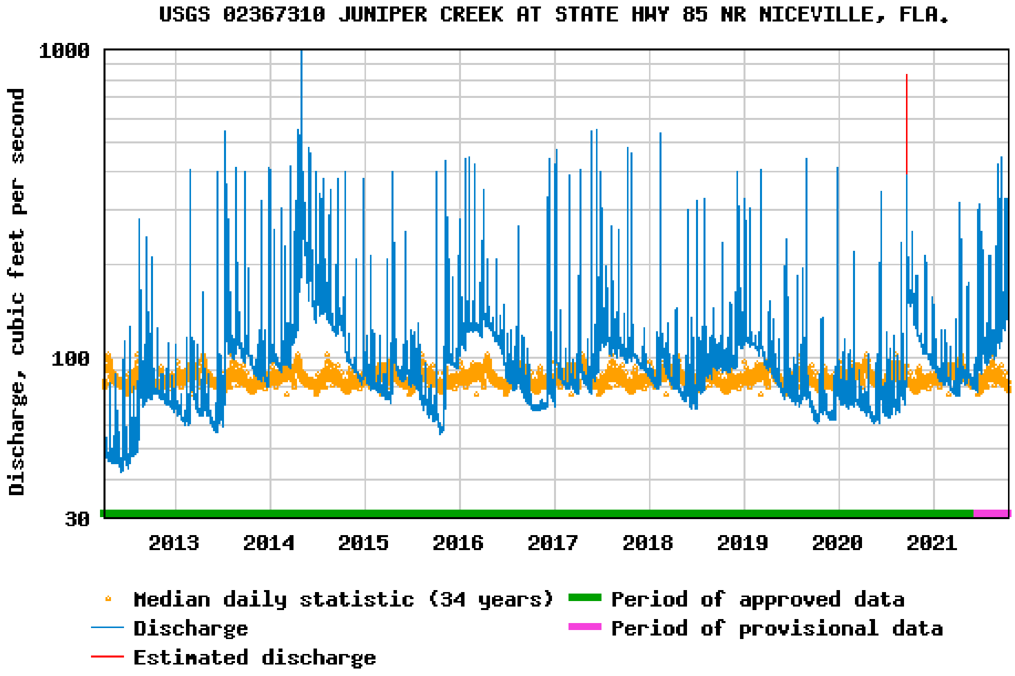


Figure 4. Discharge of Juniper Creek measured at State Highway 85, near Niceville, FL (USGS monitoring station 02367310). The lower discharges on the left are associated with an abnormally dry late winter/early spring of 2012 in northwestern Florida (National Integrated Drought Information System, 2021).

Methods

Multiple methods were used during 2020 to assess the hydrogeology, geochemistry, and hydrology of upwelling groundwater in the darter creek basins at Eglin AFB, near Niceville, FL. The methods used in this study have transferability to other military bases, especially those bases located in Gulf and Atlantic Coast states that are characterized by groundwater-dominant aquatic ecosystems.

Study Design

As was stated previously, flow in creeks inhabited by the Okaloosa darter is derived from groundwater, starting as infiltration of local precipitation to the water table, or recharge, as was recognized as early as the late 1990's (USFWS, 1998). The extent of the recharge areas that supply this groundwater, and how long it takes that recharge to reach the creeks as groundwater discharge, is not known. This study used an approach that involved the collection of groundwater samples beneath the creeks at headwater and downstream locations of each creek basin. The water samples were collected during February and December 2020, when precipitation amounts are lower to ensure the groundwater samples were not affected by precipitation or runoff. Although the focus of the study was to sample and analyze the upwelling groundwater for compounds that can be used to age-date the recharge and to determine where the recharge entered the uplands, it also provided the opportunity to collect other water-quality parameters. As such, these data also are discussed.

Creek Basins Studied

A brief description of each basin shown in Figure 2 is provided here; additional information can be found in Reeves et al (2016). The sampling sites are shown in figure 5.

Toms Creek Basin. Toms Creek drains into Toms Bayou. It is the third largest basin at 20.7 km^2 (7.99 mi^2). The headwaters are relatively unaffected by land use changes, beaver dams and ponds occur in downstream reaches. Samples for this study were collected near the headwaters and downstream side of a bridge of HWY 85 (figure 5).

Turkey Creek Basin. Turkey Creek, Parish Creek, and Juniper Creek drain into Boggy Bayou. Most of the basin is unaffected by development as it is located on Eglin AFB. Samples were collected at each headwater, and at Range Road 232 where it crosses Turkey Creek (figure 5).

Mill Creek Basin. Mill Creek drains into Boggy Bayou. It is one of the smallest drainages inhabited by Okaloosa darters at 4.6 km^2 (1.77 mi^2). The headwaters are relatively unaffected by land use changes, but the middle part flows through a golf course and then an urban area before emptying into Choctawhatchee Bay. Significant creek restoration activities have occurred within the golf course. Samples for this study were collected near the headwaters adjacent to HWY 293 and downstream side of a bridge on West College Blvd (figure 5).

Rocky Creek Basin. Rocky Creek, Exline Creek, and Bully Horselot Creek drain into Rocky Bayou. Most of the basin is unaffected by development as it is located on Eglin AFB. Samples were collected at each headwater, and at East Rocky Branch Creek at HWY 201 (figure 5).

Swift Creek Basin. Swift Creek drains into Rocky Bayou. Most of the upper part of the basin is unaffected by development as it is located on Eglin AFB but the lower part is impounded north of East College Blvd before flowing through an urban area and emptying into Rocky Bayou. Samples were collected at the headwater, downstream of the headwater but upstream of the impoundment, and at HWY 285 (figure 5).

Deer Moss Basin. Deer Moss Creek (also known as Turkey Bolton Creek) drains into Rocky Bayou. Wastewater treatment by sprayfield irrigation occurs on the plateaus on each side of the creek. The sprayfields were constructed in 1982, and between 1-2 Mgal/d of treated wastewater are applied at land surface. Samples for this study were collected near the headwaters, upstream and downstream of the sprayfield, adjacent to HWY 293 and downstream side of a bridge on Rocky Bayou Dr (figure 5).

Sites Sampled

Sites sampled in February and December 2020 are shown on figure 5. Samples were collected from below eleven headwater and eleven downgradient sites across six creek basins. Each site was named using a unique USGS station identifier and entered into the USGS National Water Information System database (U.S. Geological Survey, 2019; table 1).

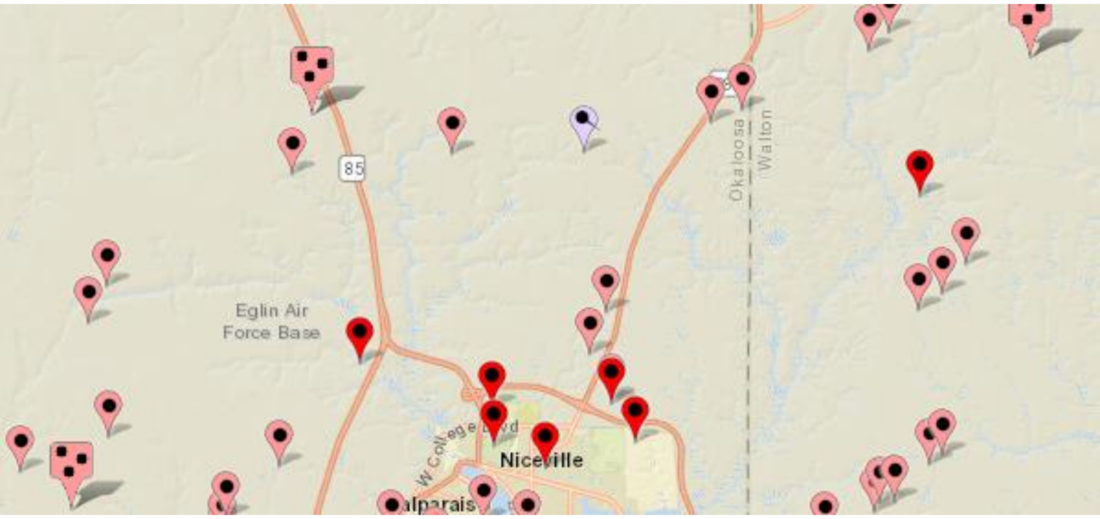


Figure 5. Groundwater sampling sites at Eglin Air Force Base, near Niceville, FL for Toms Creek, Turkey Creek, Mill Creek, Rocky Creek, Swift Creek, and Deer Moss Creek basins, February (light red symbols) and December (dark red symbols) 2020.

Table 1. Groundwater sample location name, USGS station name, and latitude and longitude, Eglin Air Force Base and surrounding area near Niceville, Florida.

Sample basin and location name	**USGS station name**	**Latitude**	**Longitude**
Tom's Creek Basin			
TOMS CREEK HEADWATERS NR VALPARAISO, FL	303144086335800	303144.3	863358.0
TOMS CREEK AT EGLIN PKWY NR VALPARAISO, FL	303023086312700	303023.2	863127.0
Turkey Creek Basin			
TURKEY CREEK HEADWATERS NR VALPARAISO, FL	303429086381400	303428.7	863814.2
PARISH CREEK HEADWATERS NR NICEVILLE, FL	303722086334200	303721.6	863341.7
JUNIPER CREEK HEADWATERS NR NICEVILLE, FL	303745086300700	303745.1	863006.6
Turkey Creek, at Range Road 232 NR NICEVILLE, FL	303342086321000	30.5617	-86.5362
Rocky Creek Basin			
EXLINE CREEK HEADWATERS NR NICEVILLE, FL	303837086233500	303836.7	862334.6
ROCKY CREEK HEADWATERS NR DEFUNIAK SPRINGS, FL	304140086180600	304139.6	861805.8
BULLY HORSELOT BRANCH HEADWATERS NR NICEVILLE, I	303537086183200	303536.7	861832.3
East Rocky Branch Creek at HWY 201 NR DUFIANK SPRIN	303656086193500	30.6155	-86.3265
Swift Creek Basin			
SWIFT CREEK SOUTH OF RUNWAY NR NICEVILLE, FL	303354086270000	303354.3	862700.3
Swift Creek, at HWY 285, near NICEVILLE, FL	303141086280000	30.528	-86.4668
Deer Moss Creek Basin			
DEER MOSS HEADWATERS AT NICEVILLE, FL	303300086263000	303259.8	862629.7
DEER MOSS HEADWATERS NR SWB1 AT NICEVILLE, FL	303256086263000	303256.1	862630.0
Deer Moss, at SWB1	303256086263000	303256.1	862630.0
Deer Moss, at SWB2	303235086263400	30.5872	-86.5613
Deer Moss, at SWB3	303225086262800	30.4094	-86.4738
Deer Moss, at SWB4	303224086262700	30.5399	-86.4409
Deer Moss, at MidBay Connector	303211086260000	30.5364	-86.4332
Deer Moss, at Rocky Bayou Drive	303045086253100	30.5125	-86.4250
Mill Creek Basin			
Mill Creek, headwater	303251086291100	30.5475	-86.4863
Mill Creek, at West College Blvd NR Niceville, FL	303206086291000	30.535	-86.486

Groundwater Head Measurements

The altitude that groundwater rose above the altitude of a particular creek sampling site was measured using a temporary well and ruler. The temporary well comprised a 16/64” bore, stainless steel rod that had mill-slot screens and a point on the bottom end, also known as a 'drivepoint' (DeepWater2 PushPoint Sampler, MHE Products). At each sampling site in the creek, a solid rod was first inserted down the well bore, and the temporary well was manually advanced such that the screen was approximately 3-4 ft below the creek bottom. The rod was removed, and groundwater entered the now hollow rod though the screen. A short piece of clear tubing was attached to the top of the open rod above the creek water level, and the altitude to which groundwater rose above the surface-water level was recorded (figure 6). This method proved to be an easy way to rapidly assess the hydrology of the creek.

Figure 6. The altitude that groundwater rises above the surface-water level can be seen in the clear tubing (in this case, about 5 inches of positive head difference) attached to the temporary well pushed 3-4 ft below the creek bed. Groundwater levels above the surface water level provided immediate confirmation that a site was characterized by groundwater discharge (gaining stream).

Groundwater and Creek Geochemistry Measurements

Water-quality parameters were measured in the field for groundwater pumped from the temporary wells as well as surface water at each sample location. Water samples were also collected for laboratory analyses.

Field Measurements

Measurements of physical properties and chemical constituents of groundwater and surface water, such as dissolved oxygen, pH, specific conductance, and temperature, were measured using an Aqua TROLL 600 Multiparameter Sonde (In-Situ, Inc.). The sonde was calibrated before each sampling day using appropriate standard methods for dissolved oxygen, pH, and specific conductance as reported in the USGS National Field Manual (U.S. Geological Survey, variously dated). The parameters were measured in groundwater pumped from the temporary well using a peristaltic pump and into a nylon graduated cylinder where the sonde was placed. Groundwater samples were collected after measurements of dissolved oxygen, pH, specific conductance, and temperature as shown by the sonde had stabilized (figure 7). Groundwater did not require filtration because of low sample turbidity. Samples of surface water were collected using the same method. Measurements of the physical properties and chemical constituents of surface water were made using the same method but placing the sonde in the creek near the bottom.

Figure 7. Upwelling groundwater from 3- to 4-ft below the creek was sampled using a peristaltic pump attached to the temporary well. A ¼-inch copper tubing and a vitex tube were used to collect the samples. The graduated nylon cylinder was used for the collection of dissolved gas samples and to house the sonde during measurements of physical properties and chemical constituents of groundwater.

Laboratory Analyses

Groundwater samples were collected for laboratory analyses of concentrations of sulfur hexafluoride (SF_6) and various dissolved gases to determine the age of the groundwater. In this report, the ‘age’ of a groundwater sample is defined as the time elapsed since the groundwater sampled first recharged the water table (in other words, the water was removed from contact with the atmosphere) using methods described by Busenberg and Plummer (1992) and using the assumption of a piston-type flow (Plummer and Friedman, 1999). The piston-type flow model conceptualizes groundwater flow as a “plug” in a single-flow tube. Under the piston-type flow model, all groundwater-flow lines are assumed to have similar velocities, and hydrodynamic dispersion and molecular diffusion are assumed to be negligible.

Sulfur Hexafluoride Concentrations

Groundwater samples were analyzed for SF_6 whose aqueous concentration reveals the date (+/- 5 years) the groundwater sample was last isolated from the atmosphere an entered the subsurface. Groundwater can be dated with SF_6 if it is in equilibrium with atmospheric SF_6 at the time of recharge, and does not contain SF_6 from other sources, such as minerals, rocks and volcanic and igneous fluids, or local anthropogenic sources such as an electrical insulator (Busenberg and Plummer, 1997). Once recharged, SF_6 behaves as an ideal gas and does not react with the substrate, sorb onto aquifer organic material, or undergo aerobic or anaerobic biodegradation. Unlike CFCs, the air-concentration curve is increasing (Figure 8), making it especially rigorous for dating groundwater younger than the mid-1990s.

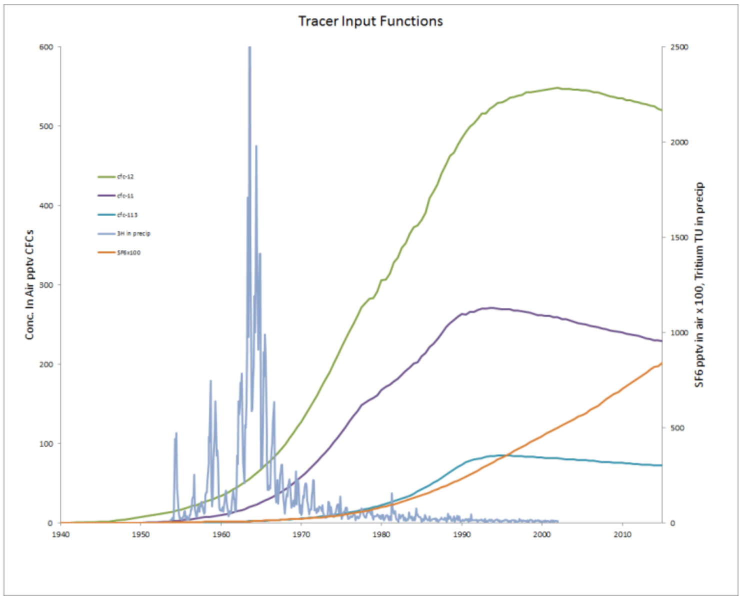


Figure 8. Atmospheric concentrations of CFCs (green, purple, and light blue lines) and SF_6 (orange line) in air of the Northern Hemisphere, in parts per thousand by volume (pptv). (Tritium concentrations are shown in light blue). As can be seen, only the line for SF_6 is increasing.

The groundwater samples for SF_6 analyses were collected using an approach designed to eliminate the interaction of the groundwater sample with ambient air during sample collection. Sample vials (1 liter [L] amber glass bottles) were filled from the bottom and allowed to overflow. Sample tubing was made of vitex or copper to eliminate contact of the sample with air during pumping, as the air concentrations are high; this is also why no samples of surface water were collected, as it is in contact with the air and, therefore, assumed to be of modern age. Each bottle was capped using a metal screw cap with an aluminum foil liner and sealed with electrical tape around the bottle caps. The sample bottles were not stored on ice but were shipped directly to the USGS Groundwater Dating Laboratory in Reston, Virginia, where the SF_6 analyses were completed in triplicate using gas chromatography/mass spectrometry.

Dissolved-Gas Concentrations

The concentrations of biologically active dissolved gases, such as methane, carbon dioxide, nitrogen, and oxygen, and the inert gas argon were measured to facilitate the interpretation of the age dates. The concentrations of dissolved nitrogen and argon can indicate the air temperature during past recharge events because the solubilities of nitrogen and argon vary substantially as a function of temperature (Weiss, 1970), as well as the presence of excess air entrained in groundwater during infiltration, movement through the unsaturated zone, and recharge. The results can also be used to interpret the redox geochemistry and as a check on the field measurements of dissolved oxygen.

The groundwater samples for dissolved-gas analyses were collected using an approach designed to eliminate the interaction of the groundwater sample with ambient air during sample collection. Sample vials (250-milliliter [mL] glass vials) were filled beneath a volume of groundwater pumped from the monitoring well into a 2-liter graduated nylon cylinder (fig. 7). The sample tubing, made of vitex or copper to eliminate contact of the sample with air during pumping, was placed in each vial under water in the cylinder. The vial was allowed to overflow and sealed under water with a rubber stopper. A 21-gauge needle was inserted into the rubber stopper until the tip slightly exited through the bottom of the stopper; the rubber stopper with the needle was inserted into the bottle while the bottle was submerged in the water in the 2-liter nylon cylinder, allowing any bubbles in the bottle to escape from the sample. The needle was removed from the stopper while the bottle was still submerged. Duplicate bottles were collected. All needles were properly disposed of or returned with the filled sample bottles. The sample name, water temperature, and estimated recharge altitude (the assumed altitude of the water table at the time of sampling) were recorded on the label attached to the foam sleeve used to protect the bottle during shipment. The samples were kept on ice or at least as cool as the temperature of the sampled groundwater to prevent the stoppers from popping because of sample warming. All sample bottles were stored upside down or on their side to keep any bubbles that formed away from the stopper. The sample bottles were shipped on ice to the USGS Groundwater Dating Laboratory in Reston, Va., where the dissolved-gas analyses were completed in duplicate using chromatograph/flame-ionization detection.

Stable Hydrogen and Oxygen Isotope Concentrations

Groundwater and surface water often have unique stable isotope values for hydrogen (H) and oxygen (O) because surface water is exposed to air and the lighter isotopes can volatilize. In contrast, groundwater tends to retain the values characteristic of recharge. Groundwater samples for stable isotope analyses of hydrogen (as delta H, or δ^2H, in per mil) and oxygen (as delta O, or δ^{18}O, in per mil) in groundwater and surface water were collected by filling 60-mL vials to almost full, capping, and then securing the cap with electrical tape. The samples were shipped to the USGS Stable Isotope Laboratory, in Reston, VA, and the stable isotopes quantified using dual-inlet isotope-ration mass spectrometry. The values for each sample were compared to each other to understand relative differences between sample location. The values also were compared to the meteoric water line of samples collected around the globe (Craig, 1961).

Recharge Extent Determinations

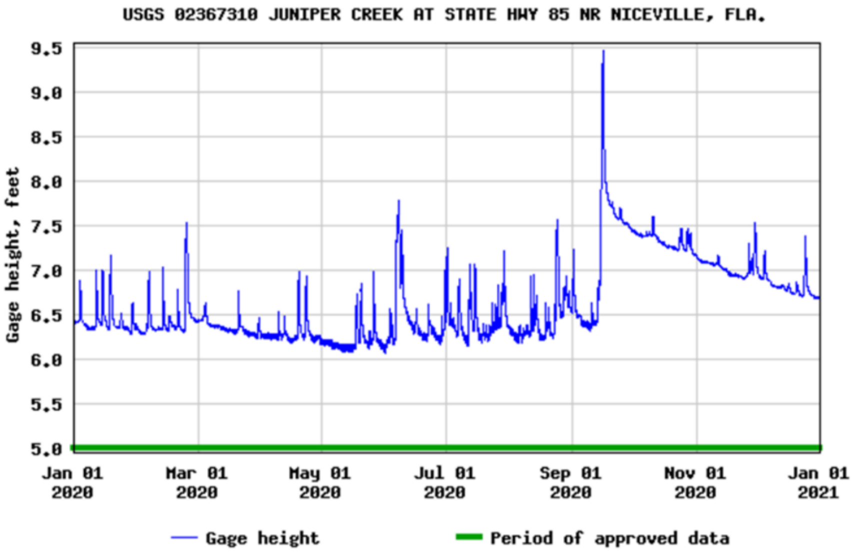
The extent from the creek sampling site where recharge would have occurred to result in the measured SF_6 concentration and, therefore age date, was determined for each site. The relation between groundwater age and recharge distance, such that L (recharge extent, in ft) = V (velocity of groundwater flow, in ft/d) * T (time since recharge, or groundwater age, in d) was used. The V was solved for by v = iK/*n*, where i is the hydraulic gradient between groundwater in upland areas (the generalized potentiometric surface from Hayes and Barr (1983) (their Figure 9, was used), K is the hydraulic conductivity, in ft/day, of the surficial aquifer (using T=Kb, such that K = T/b, where T is from Hayes and Barr (1983) (their Table 5, was used) and b is estimated (also from Hayes and Barr), and *n* is the aquifer porosity, unitless.

The recharge extents were calculated using hydraulic conductivity values of 50, 100, and 125 ft/day. This range of values are characteristic of the sand and gravel aquifer and this approach addresses the uncertainty surrounding the lack of knowledge of actual K values of the sand and gravel aquifer in the study area. The recharge extents calculated using these three values help to provide acceptable travel distances on the most probable solution; for example, all recharge extents that exceeded the known boundary of the basin were not considered. Moreover, if a particular recharge distance crossed over an adjacent creek, that solution was also discounted. The calculated recharge extent is the maximum probable distance from the creek sampling site that groundwater discharge at the creek could have entered as recharge sometime in the past. It is important to keep in mind, however, that groundwater can still be recharged all along this groundwater-flow pathway.

Results and Discussion

Flow in Creeks

Flow measurements were not made during sampling. However, contemporaneous stream gage height and discharge measurements made at the Juniper Creek site confirm that the samples collected in February and December 2020 were not influenced by recent precipitation (figure 10). Also, stream gage height and discharge are higher for December, most likely due to lower evapotranspiration (ET) (figure 10).



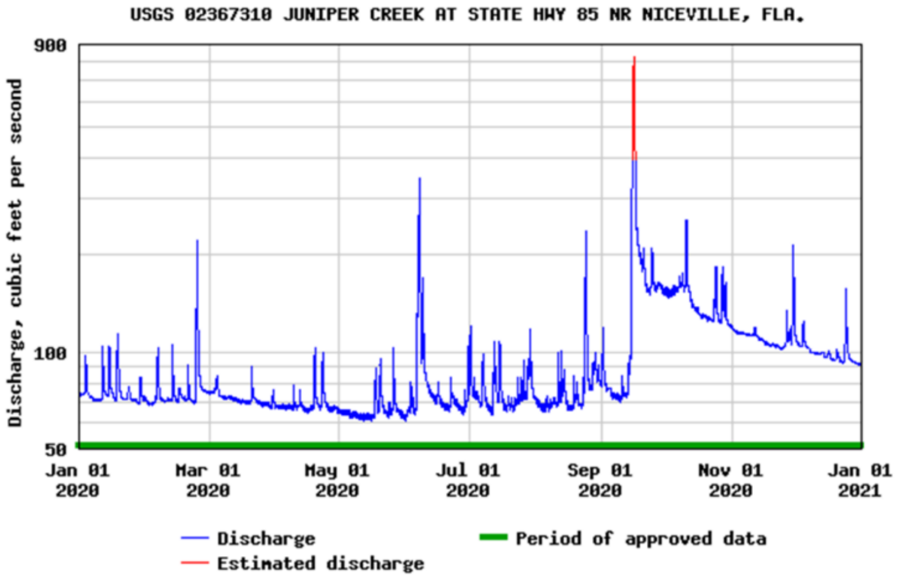


Figure 10. Stage (gage) height and discharge, in cubic feet per sec, measured at Juniper Creek during 2020 field sampling events described in this report. Stage and discharge are lower for much of the year due removal of groundwater by evapotranspiration (ET).

Groundwater Head Measurements

All 22 sites had groundwater head measurements that were above the surface-water level (table 2). These data indicate all sites are dominated by upward groundwater discharge (gaining reach). These novel head measurements provide the first data to support previous suggestions that the darter creeks are predominately supplied by groundwater (Trapp and others, 1977; Hayes and Barr, 1983; USFWS, 1998).

Table 2. Groundwater sample location name, USGS station name, latitude and longitude, sample data and time, and results of field measurements of head above altitude of creek water, Eglin Air Force Base and surrounding area near Niceville, Florida, February 4-6 and December 14-16, 2020.

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

Sample basin and location name	USGS station name	Latitude	Longitude	Sample date	Sample time	Atitude of groundwater head above creek level (inches)
Tom's Creek Basin						
TOMS CREEK HEADWATERS NR VALPARAISO, FL	303144086335800	303144.3	863358.0	February 4, 2020	1130	3.50
TOMS CREEK AT EGLIN PKWY NR VALPARAISO, FL	303023086312700	303023.2	863127.0	February 4, 2020	0925	1.50
Turkey Creek Basin						
TURKEY CREEK HEADWATERS NR VALPARAISO, FL	303429086381400	303428.7	863814.2	February 4, 2020	1400	4.50
PARISH CREEK HEADWATERS NR NICEVILLE, FL	303722086334200	303721.6	863341.7	February 4, 2020	1530	4.50
JUNIPER CREEK HEADWATERS NR NICEVILLE, FL	303745086300700	303745.1	863006.6	February 4, 2020	1815	2.50
Turkey Creek, at Range Road 232 NR NICEVILLE, FL	303342086321000	30.5617	-86.5362	December 16, 2020	811	0.5
Rocky Creek Basin						
EXLINE CREEK HEADWATERS NR NICEVILLE, FL	303837086233500	303836.7	862334.6	February 5, 2020	0900	3.25
ROCKY CREEK HEADWATERS NR DEFUNIAK SPRINGS, FL	304140086180600	304139.6	861805.8	February 5, 2020	1110	4.50
BULLY HORSELOT BRANCH HEADWATERS NR NICEVILLE,	303537086183200	303536.7	861832.3	February 5, 2020	1430	3.00
East Rocky Branch Creek at HWY 201 NR DUFIANK SPRIN	303656086193500	30.6155	-86.3265	December 14, 2020	1634	2.00
Swift Creek Basin						
SWIFT CREEK SOUTH OF RUNWAY NR NICEVILLE, FL	303354086270000	303354.3	862700.3	February 5, 2020	1630	9.50
Swift Creek, at HWY 285, near NICEVILLE, FL	303141086280000	30.528	-86.4668	December 15, 2020	1446	3.5
Deer Moss Creek Basin						
DEER MOSS HEADWATERS AT NICEVILLE, FL	303300086263000	303259.8	862629.7	February 6, 2020	0840	6.00
DEER MOSS HEADWATERS NR SWB1 AT NICEVILLE, FL	303256086263000	303256.1	862630.0	February 6, 2020	1000	4.00
Deer Moss, at SWB1	303256086263000	303256.1	862630.0	December 15, 2020	1248	0.75
Deer Moss, at SWB2	303235086263400	30.5872	-86.5613	December 15, 2020	1016	8.00
Deer Moss, at SWB3	303225086262800	30.4094	-86.4738	December 15, 2020	1109	3.50
Deer Moss, at SWB4	303224086262700	30.5399	-86.4409	December 15, 2020	1334	14.00
Deer Moss, at MidBay Connector	303211086260000	30.5364	-86.4332	December 14, 2020	1112	1.00
Deer Moss, at Rocky Bayou Drive	303045086253100	30.5125	-86.4250	December 15, 2020	840	5.00
Mill Creek Basin						
Mill Creek, headwater	303251086291100	30.5475	-86.4863	December 14, 2020	841	0.50
Mill Creek, at West College Blvd NR Niceville, FL	303206086291000	30.535	-86.486	December 15, 2020	1526	1.5

The magnitude of groundwater head above surface water was greater at headwater sites and lower in downgradient sites in those basins characterized by a natural flow regime (table 2). These basins include Toms Creek, Turkey Creek, and Rocky Creek. For those basins characterized by an intermediate flow regime (some natural flow and some artificially impacted flow), such as Swift Creek, groundwater head above surface water was greater in the headwaters upstream of the dam at East College Blvd) and lower in the downgradient location. The same scenario was observed in the sprayfield-impacted basin of Deer Moss Creek, where groundwater head above surface water was greater in the headwaters and lower in downgradient locations; however, the greatest groundwater head was measured in the middle reach, due to the input of treated water from sprayfields located in the uplands on each bank. In contrast to these basins, groundwater head above surface water was lower in the headwaters and higher in the downgradient location in the golf course impacted basin of Mill Creek.

The observation of higher altitudes of groundwater in the headwaters at most sites reveals two possible properties of the surficial part of the sand and gravel aquifer. First, assuming equal recharge occurs across all sites, the hydraulic conductivity of the sand and gravel aquifer that drains to the headwaters (inland parts) of each basin would necessarily be lower than the hydraulic conductivity of the aquifer that drains to the lower part of each basin. In other words, rates of groundwater flow would be faster in the sand and gravel aquifer beneath the lower reaches and groundwater-flow rates slower in the headwaters. This would indicate that recharge extent is farther from the groundwater sample collection site in the headwaters of each stream, even without having any age dating results. If confirmed, this difference in head (as the equipotential line of 3.5 ft) may also be correlated to the demarcation between the sandhills of the inland Western Highlands physiographic region and the Gulf Coastal Lowlands (plotted as figure 3 in Hayes and Barr, 1983) (figure 11). Alternatively, if it is assumed that recharge is higher in the natural, undeveloped uplands that surround the headwaters and lower (or reduced by some man-made or natural obstacles) in the downgradient reaches, groundwater-flow rates would be essentially constant across all basins.

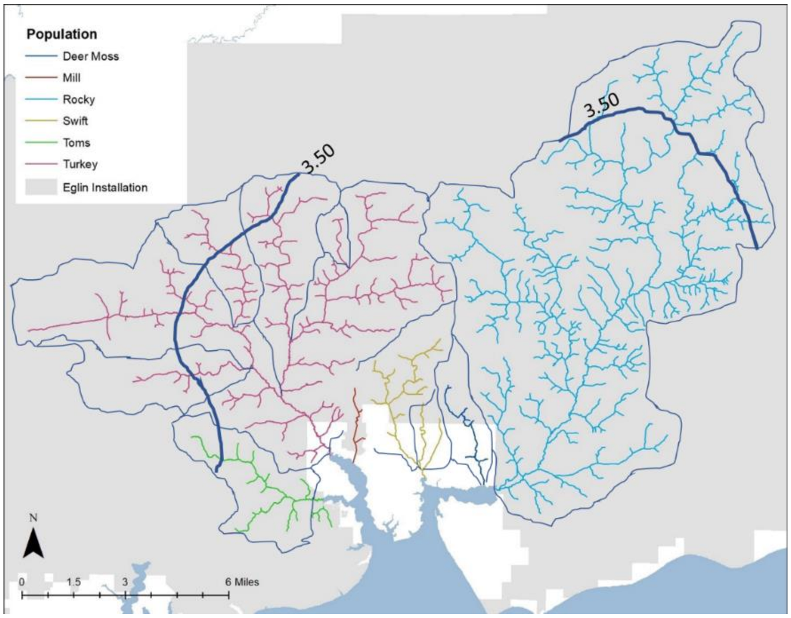


Figure 11. Map of equihead line (3.5 ft of head above the surface-water level) that may be correlated to the demarcation between the sandhills of the inland Western Highlands physiographic region and the Gulf Coastal Lowlands.

Groundwater and Creek Geochemistry Measurements

Field Measurements

Dissolved Oxygen

In general, groundwater upwelling to headwaters of the six darter basins had higher concentrations of dissolved oxygen (1.37-9.24 mg/L, avg = 4) compared to lower DO concentrations measured farther downstream (0.86-2.33 mg/L, avg = 1) (table 3). Dissolved oxygen in groundwater had entered during recharge of oxygen-saturated (8.0 mg/L at 25 ˚C) precipitation. Measurement of dissolved oxygen near 8 mg/L in groundwater upwelling to creeks after some distance of transport underground indicates little biological or mineral oxygen demand exists in those parts of the sand and gravel aquifer. In contrast, lower dissolved oxygen concentrations measured in groundwater indicate sinks for dissolved oxygen, such as respiration by aerobic heterotrophic bacteria, exist in the aquifer formation material or the removal is caused by mineral (e.g., Fe(II)) oxidation. In contrast, dissolved oxygen concentrations in surface water were consistently greater than 7.90 mg/L at all 22 sites, even where upwelling groundwater was observed to be much lower. These consistently higher levels of dissolved oxygen are due to aeration of surface water by exposure to the atmosphere which contains 20 percent oxygen.

Table 3 . Sample location name, USGS station name, latitude and longitude, sample data and time, and results of field measurements of physical properties and chemical composition, Eglin Air Force Base and surrounding area near Niceville, Florida, February 4-6 and December 14-16, 2020.

[GW, groundwater; SW, surface water; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, millirgams per liter; average values for each measurement area shown in bold at bottom of column]

Sample location name	**USGS station name**	**Latitude**	**Longitude**	**Sample date**	**Sample time**	**Sample type (GW or SW)**	**Temperature (°C)**	**Specific conductance (µS/cm)**	**pH**	**Dissolved oxygen (mg/L)**	**Wastewater treatment compounds (ug/L)**	**Comments**
Tom's Creek Basin												
TOMS CREEK HEADWATERS NR VALPARAISO, FL	303144086335800	303144.3	863358.0	February 4, 2020	1124	GW	21.09	16.42	5.18	8.47		Clear
					1130	SW	20.75	15.32	4.84	8.28		
TOMS CREEK AT EGLIN PKWY NR VALPARAISO, FL	303023086312700	303023.2	863127.0	February 4, 2020	0925	GW	15.6	125	6.39	1		GW turbid
					815	SW	14.95	23	5.89	9.03		
Turkey Creek Basin												
TURKEY CREEK HEADWATERS NR VALPARAISO, FL	303429086381400	303428.7	863814.2	February 4, 2020	1400	GW	21.02	12.89	5.03	8.61		About 800 yards downstream of headwater
					1400	SW	21.16	14.8	5.06	8.59		
PARISH CREEK HEADWATERS NR NICEVILLE, FL	303722086334200	303721.6	863341.7	February 4, 2020	1530	GW	20.76	16.11	5.00	8.64		About 400 yards downstream of
					1533	SW	20.42	12.18	5.02	8.35		
JUNIPER CREEK HEADWATERS NR NICEVILLE, FL	303745086300700	303745.1	863006.6	February 4, 2020	1815	GW	20.41	14.72	4.88	6.60		Headwater east 175 yds be
						SW	19.6	11.15	5.01	8.03		
Turkey Creek, at Range Road 232	303342086321000	30.5617	-86.5362	December 16, 2020	850	GW	15.29	69.39	4.07	0.86		
					811	SW	16.12	13.5	4.53	9.30		
Rocky Creek Basin												
EXLINE CREEK HEADWATERS NR NICEVILLE, FL	303837086233500	303836.7	862334.6	February 5, 2020	915	GW	21.17	17.36	5.15	8.71		
					853	SW	20.18	13.84	5.00	8.80		
ROCKY CREEK HEADWATERS NR DEFUNIAK SPRINGS, FL	304140086180600	304139.6	861805.8	February 5, 2020	1118	GW	20.17	16.34	4.81	2.64		
					1100	SW	19.1	13.88	4.60	8.39		
BULLY HORSELOT BRANCH HEADWATERS NR NICEVILLE,	303537086183200	303536.7	861832.3	February 5, 2020	1435	GW	19.38	14.82	5.06	9.24		About 800 yards downstream of
					1415	SW	18.21	14.85	5.02	8.41		Bubbled gas (CO2?)
East Rocky Branch Creek at HWY 201	303656086193500	30.6155	-86.3265	December 14, 2020	1634	GW	17.73	50.95	5.60	1.97		H2S odor
					1634	SW	18.46	10.48	5.73	8.94		
Swift Creek Basin												
SWIFT CREEK SOUTH OF RUNWAY NR NICEVILLE, FL	303354086270000	303354.3	862700.3	February 5, 2020	1630	GW	20.55	19.13	5.07	8.83		About 900 yards downstream of
					1615	SW	20.42	18.5	5.81	8.39		
Swift Creek, at HWY 285	303141086280000	30.528	-86.4668	December 15, 2020	1446	GW	17.13	55.18	5.53	2.46		
						SW	17.06	27.5	6.18	9.18		
Deer Moss Basin												
DEER MOSS HEADWATERS AT NICEVILLE, FL	303300086263000	303259.8	862629.7	February 6, 2020	845	GW	20.92	17.61	4.88	6.73		About 30 yards downstream of headwater. Very
					835	SW	20.40	16.36	4.93	7.90		
DEER MOSS HEADWATERS NR SWB1 AT NICEVILLE, FL	303256086263000	303256.1	862630.0	February 6, 2020	955	GW	21.03	18.07	4.94	5.17		Not as clear as previous sample.Below spray field.
					945	SW	20.54	16.24	4.94	8.05		
Deer Moss, at SWB1	303256086263000	303256.1	862630.0	December 15, 2020	1248	GW	19.1	20.78	5.07	6.52	ND	
					1248	SW	18.95	17.86	5.18	8.27		
Deer Moss, at SWB2	303235086263400	30.5872	-86.5613	December 15, 2020	1022	GW	18.93	468	5.56	7.84	Tribromomethane (bromoform); triethyl citrate (perfume)	
					1016	SW	17.78	73.23	5.70	8.69		
Deer Moss, at SWB3	303225086262800	30.4094	-86.4738	December 15, 2020	1109	GW	18.63	252.03	5.88	7.04	Triethyl citrate (perfume)	
					1111	SW	18.11	101.59	6.60	8.54		
Deer Moss, at SWB4	303224086262700	30.5399	-86.4409	December 15, 2020	1334	GW	19.97	28.64	5.48	3.38	n,n-dimethyl-m-toluamide (DEET)	"hog waller"
						SW	18.87	21.04	5.73	8.47		
Deer Moss, at MidBay Connector	303211086260000	30.5364	-86.4332	December 14, 2020	1146	GW	18.94	60.11	5.24	1.12	ND	H2S odor
					1112	SW	18.96	104.19	6.57	8.81		
Deer Moss, at Rocky Bayou Drive	303045086253100	30.5125	-86.4250	December 15, 2020	853	GW	13.68	47.18	5.18	2.33		
					840	SW	13.1	80.99	6.66	9.46		
Mill Creek Basin												
Mill Creek, headwater	303251086291100	30.5475	-86.4863	December 14, 2020	852	GW	17.82	18.22	3.94	1.37		
					841	SW	18.29	21.38	4.34	7.76		
Mill Creek, at College Blvd	303206086291000	30.535	-86.486	December 15, 2020	1526	GW	18.37	119.52	5.84	0.97		
						SW	17.3	39.05	6.18	8.55		

Specific Conductance

In general, the specific conductance values in groundwater are low (table 3). This is because precipitation has little to no mineral content (i.e., is dilute) and it then flows through the leached sands of the sand and gravel aquifer of little remaining solubility. There is a trend of increasing specific conductance in groundwater from headwater sites (12.89-19.13 µs/cm, avg = 15) to downstream sites (14.72-125 µs/cm, avg 90) (table 3). This increase may reflect more input to groundwater from man-made sources at land surface. The specific conductance of surface water decreased downstream in Turkey Creek and Rocky Creek basins. The highest specific conductance in groundwater (4,698 µs/cm) was for Deer Moss Creek where upwelling groundwater was impacted by groundwater that contained sprayfield leachate coming from both sides of the creek.

pH

The pH of groundwater and steams is less than 7 and acidic (table 3). Groundwater pH ranges from 3.94 to 6.39. Surface water pH ranges from 4.34 to 6.66. The groundwater pH is lower due to little natural mineral buffering capacity of the aquifer and input of carbon dioxide from natural aerobic metabolism of organic matter and root respiration. In contrast, surface water pH is slightly higher as carbon dioxide volatilizes from the water surface to the atmosphere as the water flows downstream over a rough terrain.

In Toms Creek, Swift Creek, and Mill Creek basins, the pH of groundwater and surface water are lower in the headwaters and higher downstream (table 3). The pH of the groundwater and surface water at the headwater sampling site of Mill Creek was the lowest measured at any site. This site is the only location surrounded by a golf course.

In Deer Moss Basin, the pH increases from lows at the headwaters to downstream sites (table 3). The pH increases mid-reach due to the input of infiltrated sprayfield leachate reaching the creek at these locations. These were some of the highest pHs measured in surface water, and the higher pHs persisted downstream away from the direct interaction with sprayfield leachate.

Groundwater and Surface-Water Temperature

Groundwater is slightly warmer than surface water in the headwaters at most sites (February data only) (table 3). This is because groundwater is isolated from the daily and seasonal changes in air temperature that affect surface water. Higher temperatures are observed for both groundwater and surface water (February and December data) at the headwater sites with a trend of decreasing temperature with distance downstream for all basins except Mill Creek. The lowest temperatures measured for groundwater and surface water were at the downstream site of Deer Moss basin.

Laboratory Analyses

SF_6 and Piston-Flow Model Recharge Age

The concentrations of SF_6 ranged from 0.95 to 3.28 fMol/L (femtomoles per liter) (table 4). Higher concentrations are directly related to younger water (see figure 8), and ages of upwelling groundwater ranged from 5 to 28.6 years across all sites. As such, piston-flow model recharge ages computed using TracerLPM (Jurgens and others, 2012) ranged from as recent as 2016 to as old as mid-1991.

Table 4. Concentrations of SF_6 in groundwater samples and apparent groundwater age dates, sand and gravel aquifer, Eglin AFB, near Niceville, FL, Feb 4-6 and December 14-16, 2020

				[fMol/L, Femtomole per liter]			
Sample basin and location name	**USGS station name**	**Sample date**	**Sample time**	**Concentration in water (fMol/L), lowest of two samples shown**	**Piston-type flow model**		
Tom's Creek Basin					**Recharge year**	**Recharge age, years before sample collection**	
TOMS CREEK HEADWATERS NR VALPARAISO, FL	303144086335800	February 4, 2020	1130	0.95	1991.5	28.6	–
TOMS CREEK AT EGLIN PKWY NR VALPARAISO, FL	303023086312700	February 4, 2020	0925	1.97	2012	8.1	–
Turkey Creek Basin							
TURKEY CREEK HEADWATERS NR VALPARAISO, FL	303429086381400	February 4, 2020	1400	1.98	2002.0	18.1	–
PARISH CREEK HEADWATERS NR NICEVILLE, FL	303722086334200	February 4, 2020	1530	1.80	2001.0	19.1	–
JUNIPER CREEK HEADWATERS NR NICEVILLE, FL	303745086300700	February 4, 2020	1815	1.54	1996.5	23.6	–
Turkey Creek, at Range Road 232 NR NICEVILLE, FL	303342086321000	December 16, 2020	850	0.89	2004.5	16.5	–
Rocky Creek Basin							
EXLINE CREEK HEADWATERS NR NICEVILLE, FL	303837086233500	February 5, 2020	0900	1.22	1995.0	25.1	–
ROCKY CREEK HEADWATERS NR DEFUNIAK SPRINGS, FL	304140086180600	February 5, 2020	1110	2.21	2004.0	16.1	–
BULLY HORSELOT BRANCH HEADWATERS NR NICEVILLE, FL	303537086183200	February 5, 2020	1430	1.27	1995.5	24.6	
East Rocky Branch Creek at HWY 201 NR DUFIANK SPRINGS, FL	303656086193500	December 14, 2020	1634	3.28	2016.0	5	One bottle cracked and not analyzed
Swift Creek Basin							
SWIFT CREEK SOUTH OF RUNWAY NR NICEVILLE, FL	303354086270000	February 5, 2020	1630	2.03	2007.5	12.6	–
Swift Creek, at HWY 285, near NICEVILLE, FL	303141086280000	December 15, 2020	1446	1.53	1998.5	22.5	–
Deer Moss Creek Basin							
DEER MOSS HEADWATERS AT NICEVILLE, FL	303300086263000	February 6, 2020	0840	2.19	2005.5	14.6	–
DEER MOSS HEADWATERS NR SWB1 AT NICEVILLE, FL	303256086263000	February 6, 2020	1000	2.15	2008.5	11.6	One bottle only
Deer Moss, at MidBay Connector	303211086260000	December 14, 2020	1146	1.43	1998	23	–
Mill Creek Basin							
Mill Creek, headwater	303251086291100	December 14, 2020	852	2.43	2007.5	13.5	–
Mill Creek, at West College Blvd NR Niceville, FL	303206086291000	December 15, 2020	1526	1.49	1996	25	One bottle broken during shipping

For Toms Creek, Turkey Creek, and Rocky Creek (the natural flow regimes), the headwaters were characterized by older groundwater with younger groundwater limited to downstream areas (table 4). In contrast, Mill Creek, Swift Creek, and Deer Moss Creek basins headwaters were characterized by relatively younger water, with older groundwater downstream. These latter three basins are smaller and more isolated by adjacent stream capture than the larger basins. Moreover, these three basins are more impacted by man-made land uses compared to the larger three basins. The implications of the distribution of groundwater ages in relation to recharge extent and darter management are discussed in the "Recharge Extent and Management Implications" section.

Dissolved Gases

Methane was not detected in groundwater in any of the headwater sites, with the single exception of a trace of methane at the headwaters of impacted Mill Creek (table 5). Oxygen detection was the inverse of methane. The lack of methane and presence of dissolved oxygen in these groundwater samples supports the oxic-rich groundwater measured at these headwater locations. In contrast, the methane was detected in all downgradient locations, characterized by lower concentrations of dissolved oxygen (table 5). The highest concentrations of carbon dioxide were detected in these downgradient sites, suggesting the mineralization of either natural or contaminant organic compounds via aerobic or facultatively-anaerobic degradation. The concentrations of nitrogen, as nitrogen gas, were similar across all sites and probably reflect the absorption of nitrogen gas from the atmosphere (78 percent) into the water at time of recharge (groundwater) or sampling (surface water); the solubility of nitrogen (N_2) in water at 20˚C is about 20 mg/L. The concentrations of argon were used as part of the input to TracerLPM, as previously described.

Table 5. Concentrations of methane, carbon dioxide, nitrogen, oxygen, and argon in groundwater samples, Eglin AFB, near Niceville, Florida, February and December, 2020

[°C, Celsius; ft amsl, feet above mean sea level; mg/L., milligrams per liter; values shown are the average of duplicate samples]

						Concentration, in mg/L*				
Sample basin and location name	**USGS station name**	**Sample date**	**Sample time**	**Recharge altitude, ft amsl**	**Groundwater temperature, C**	**Methane (CH_4)**	**Carbon dioxide (CO_2)**	**Nitrogen (N_2)**	**Oxygen (O_2)**	**Argon (Ar)**
Tom's Creek Basin										
TOMS CREEK HEADWATERS NR VALPARAISO, FL	303144086335800	February 4, 2020	1130	111	21.09	0.0000	12.3414	16.4846	8.0468	0.5934
TOMS CREEK AT EGLIN PKWY NR VALPARAISO, FL	303023086312700	February 4, 2020	0925	150	15.6	5.7017	24.5601	13.2505	0.2416	0.5223
Turkey Creek Basin										
TURKEY CREEK HEADWATERS NR VALPARAISO, FL	303429086381400	February 4, 2020	1400	150	21	0.0000	9.9364	17.7163	8.9063	0.6112
PARISH CREEK HEADWATERS NR NICEVILLE, FL	303722086334200	February 4, 2020	1530	200	20.8	0.0000	18.3223	17.3609	8.8681	0.6043
JUNIPER CREEK HEADWATERS NR NICEVILLE, FL	303745086300700	February 4, 2020	1815	190	14.72	0.0000	24.2641	17.9197	6.3138	0.6314
Turkey Creek, at Range Road 232 NR NICEVILLE, FL	303342086321000	December 16, 2020	850	180	15.29	12.7356	199.1350	9.6246	0.0995	0.3795
Rocky Creek Basin										
EXLINE CREEK HEADWATERS NR NICEVILLE, FL	303837086233500	February 5, 2020	0900	200	20.15	0.0000	26.0796	16.7890	8.5986	0.6114
ROCKY CREEK HEADWATERS NR DEFUNIAK SPRINGS,	304140086180600	February 5, 2020	1110	250	20.2	0.0000	29.7975	17.8582	2.2822	0.6249
BULLY HORSELOT BRANCH HEADWATERS NR NICEVIL	303537086183200	February 5, 2020	1430	200	19.4	0.0000	19.8668	16.9517	7.8828	0.6116
East Rocky Branch Creek at HWY 201 NR DUFIANK SP	303656086193500	December 14, 2020	1634	110	17.73	5.4162	83.0419	16.3902	0.0901	0.5296
Swift Creek Basin										
SWIFT CREEK SOUTH OF RUNWAY NR NICEVILLE, FL	303354086270000	February 5, 2020	1630	150	20.6	0.0000	12.7834	15.9430	8.5143	0.5784
Swift Creek, at HWY 285, near NICEVILLE, FL	303141086280000	December 15, 2020	1446	110	17.13	2.1476	88.9335	17.1060	0.0894	0.6158
Deer Moss Creek Basin										
DEER MOSS HEADWATERS AT NICEVILLE, FL	303300086263000	February 6, 2020	0840	150	20.9	0.0000	14.8922	17.0865	6.3837	0.5978
DEER MOSS HEADWATERS NR SWB1 AT NICEVILLE, Fl	303256086263000	February 6, 2020	1000	150	21.03	0.0000	17.5910	16.0855	5.3003	0.5777
Deer Moss, at MidBay Connector	303211086260000	December 14, 2020	1146	110	18.96	1.7464	34.0386	16.0155	0.0885	0.5659
Mill Creek Basin										
Mill Creek, headwater	303251086291100	December 14, 2020	852	120	17.82	0.1908	43.6960	17.4210	0.0843	0.6320
Mill Creek, at West College Blvd NR Niceville, FL	303206086291000	December 15, 2020	1526	110	18.37	2.7782	58.8051	17.1444	0.0874	0.5433

Stable Hydrogen and Oxygen Isotope Concentrations

The stable isotopes for groundwater samples collected in February (table 6) are shown in Figure 12. All samples plot above the global meteoric water line (Craig, 1961) and reflects slightly heavier (enriched in percent heavier isotope) δ^2H values characteristic of regional precipitation rapidly removed from the atmosphere following recharge. The isotopically heaviest samples (less negative values for δ^2H and $\delta^{18}O$) were collected at two of the three headwater sites (Parrish and Turkey Creeks) of the same basin. This basin is located farthest to the west in the study area and is characterized by extensive groundwater sapping and older groundwater (table 4).

Table 6. Groundwater sample location name, USGS station name, latitude and longitude, sample data and time, and results of stable hydrogen and oxygen isotopes, Eglin Air Force Base and surrounding area near Niceville, Florida, February 4-6, 2020.

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; δ, del in per mil]

Sample basin and location name	**USGS station name**	**Sample date**	**Sample time**	**δ^2H**	**δ^{18}O**
Tom's Creek Basin					
TOMS CREEK HEADWATERS NR VALPARAISO, FL	303144086335800	February 4, 2020	1130	-19.28	-3.87
TOMS CREEK AT EGLIN PKWY NR VALPARAISO, FL	303023086312700	February 4, 2020	0925	-20.24	-4.04
Turkey Creek Basin					
TURKEY CREEK HEADWATERS NR VALPARAISO, FL	303429086381400	February 4, 2020	1400	-16.12	-3.48
PARISH CREEK HEADWATERS NR NICEVILLE, FL	303722086334200	February 4, 2020	1530	-17.73	-3.63
JUNIPER CREEK HEADWATERS NR NICEVILLE, FL	303745086300700	February 4, 2020	1815	-20.21	-3.83
Rocky Creek Basin					
EXLINE CREEK HEADWATERS NR NICEVILLE, FL	303837086233500	February 5, 2020	0900	-20.16	-3.93
ROCKY CREEK HEADWATERS NR DEFUNIAK SPRINGS, FL	304140086180600	February 5, 2020	1110	-20.34	-3.96
BULLY HORSELOT BRANCH HEADWATERS NR NICEVILLE,	303537086183200	February 5, 2020	1430	-19.28	-3.83
Swift Creek Basin					
SWIFT CREEK SOUTH OF RUNWAY NR NICEVILLE, FL	303354086270000	February 5, 2020	1630	-20.95	-3.99
Deer Moss Creek Basin					
DEER MOSS HEADWATERS AT NICEVILLE, FL	303300086263000	February 6, 2020	0840	-19.74	-3.90
DEER MOSS HEADWATERS NR SWB1 AT NICEVILLE, FL	303256086263000	February 6, 2020	1000	-21.54	-4.10

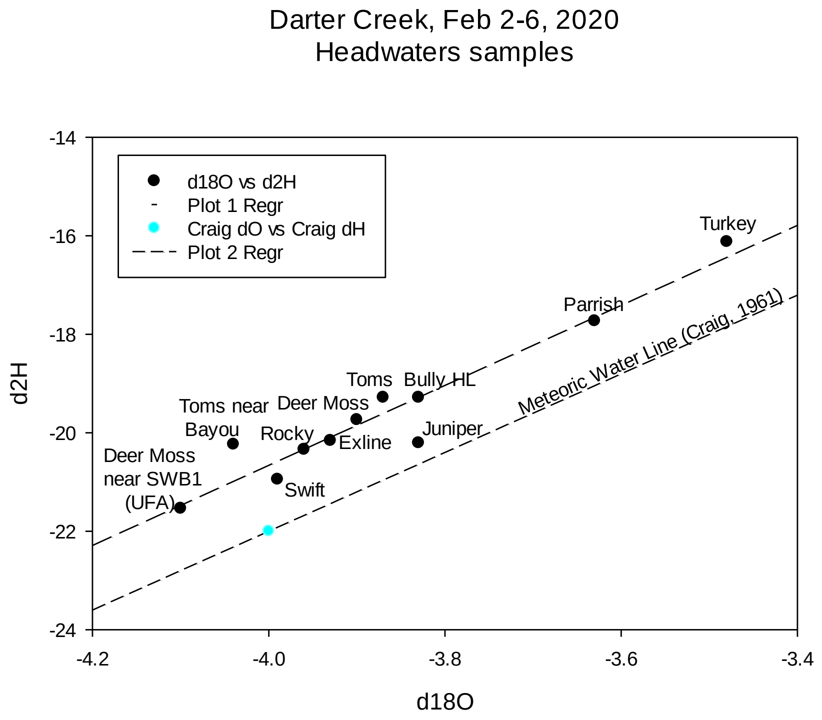


Figure 12. Stable hydrogen (as δ^{2}H) and oxygen (as δ^{18}O) data collected at Eglin Air Force Base, near Niceville, FL, February 4-6, 2020. The data for each sampling site are plotted (long dash) in relation to the meteoric water line of values of water collected around the globe (short dash).

Recharge Extent

The calculated recharge extents from each site are shown in table 7 and plotted in Figure 13A-K. When combined with representative values of hydraulic conductivity for the sand and gravel aquifer, the ages reveal that the recharge occurred from about 730 to about 6,600 feet from the creeks. For most sites, recharge was located farther from the creek in headwaters compared to sites located downstream. Recharge area was also greater for headwaters and was more arrow for downstream sites.

Table 7 - Calculated recharge extents, or distance from the sampling site to upland areas, Eglin Air Force Base, near Niceville, FL

Sites samples in February and December, 2020											SF_6	SF_6	Length if	Length if
Site name	i (ft/ft)	K (ft/d)	K (ft/d)	K (ft/d)	n	Velocity (ft/d), where V= iK/n, K=100	Velocity (ft/d), where V= iK/n, K=50	Velocity (ft/d), where V= iK/n, K=125	Time (SF_6-based age date)	SF_6 years to days	Length, ft upgradient from sampling point in stream, K=100	Length, miles upgradient from sampling point in stream	K=50	K=125
Tom's Creek Basin														
Tom's Creek Headwaters Confluence	0.002	100	50	125	0.25	0.8	0.4	1	28.6	10439	8351.2	1.581667	4175.6	10439
Tom's Creek Site 23, Eglin Parkway	0.002	100	50	125	0.25	0.8	0.4	1	8.1	2956.5	2365.2	0.447955	1182.6	2956.5
Turkey Creek Basin														
Turkey Creek 34	0.002	100	50	125	0.25	0.8	0.4	1	18.1	6606.5	5285.2	1.000985	2642.6	6606.5
Parrish Creek, upstream of 48, 400 yds downstream of headwaters	0.002	100	50	125	0.25	0.8	0.4	1	19.1	6971.5	5577.2	1.056288	2788.6	6971.5
Juniper Creek Headwaters East 175 yds downstream of head	0.002	100	50	125	0.25	0.8	0.4	1	23.6	8614	6891.2	1.305152	3445.6	8614
Turkey Creek at Range road 232	0.002	100	50	125	0.25	0.8	0.4	1	16.5	6022.5	4818	0.9125	2409	6022.5
Rocky Creek Basin														
Elxline Creek Headwaters	0.002	100	50	125	0.25	0.8	0.4	1	25.1	9161.5	7329.2	1.388106	3664.6	9161.5
Rocky Creek Headwaters	0.002	100	50	125	0.25	0.8	0.4	1	16.1	5876.5	4701.2	0.890379	2350.6	5876.5
Bully Horselot Branch	0.002	100	50	125	0.25	0.8	0.4	1	24.6	8979	7183.2	1.360455	3591.6	8979
East Rocky Creek at HWY 201	0.002	100	50	125	0.25	0.8	0.4	1	5	1825	1460	0.276515	730	1825
Swift Creek Basin														
Swift Creek at Runway	0.002	100	50	125	0.25	0.8	0.4	1	12.6	4599	3679.2	0.696818	1839.6	4599
Swift Creek at HWY285	0.002	100	50	125	0.25	0.8	0.4	1	22.5	8212.5	6570	1.244318	3285	8212.5
Deer Moss Basin											0			
Deer Moss Headwaters	0.002	100	50	125	0.25	0.8	0.4	1	14.6	5329	4263.2	0.807424	2131.6	5329
Deer Moss Headwaters SWB1	0.002	100	50	125	0.25	0.8	0.4	1	11.6	4234	3387.2	0.641515	1693.6	4234
Deer Moss at MidBay Connector	0.002	100	50	125	0.25	0.8	0.4	1	23	8395	6716	1.27197	3358	8395
Mill Creek Basin														
Mill Creek, headwaters	0.002	100	50	125	0.25	0.8	0.4	1	13.5	4927.5	3942	0.746591	1971	4927.5
Mill Creek at West College BLVD	0.002	100	50	125	0.25	0.8	0.4	1	25	9125	7300	1.382576	3650	9125

The recharge extent for the headwater of Toms Creek basin was calculated to be approximately 4,180 ft from the sampling site (table 7, figure 13A). The area of recharge estimated covers a broad upland area. In contrast, the recharge extent calculated for a downstream location of Toms Creek was only about 1,200 ft from the sampling site and limited to a narrow extent on either side of the creek (for all downstream sites sampled, it is not known which side of the creek the groundwater sample was ultimately derived from, so both sides are shown.)

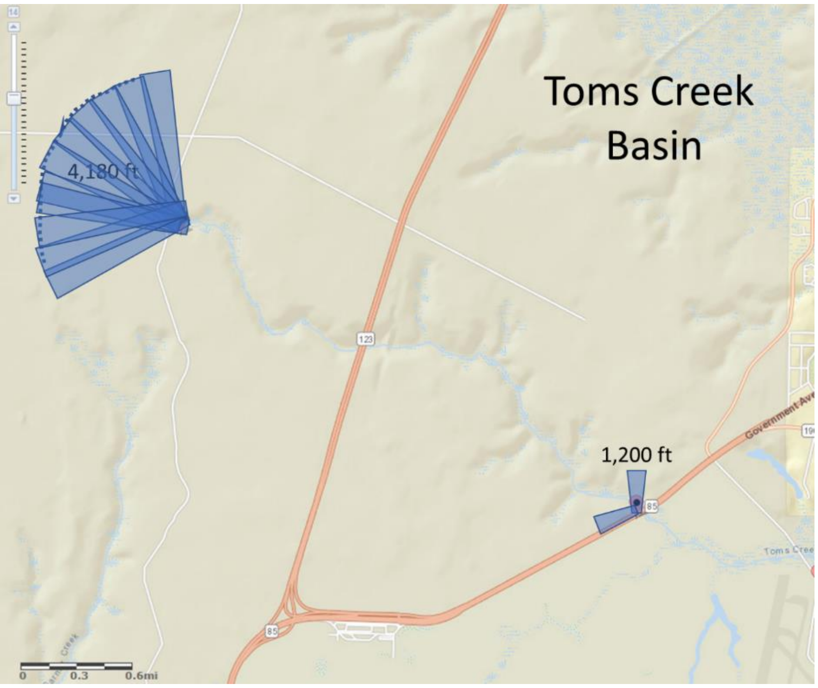


Figure 13A. The recharge extent for the headwater of Toms Creek basin was calculated to be approximately 4,180 ft from the sampling site (table 7). The recharge extent calculated for the downstream location of Toms Creek was only about 1,200 ft from the sampling site and limited to a narrow extent on either side of the creek, February and December 2020, Eglin Air Force Base, near Niceville, FL.

The recharge extent for the headwaters of Turkey Creek basin was calculated to be about 4,180 ft for Turkey Creek, 5,580 ft for Parrish Creek, and 3,450 ft for Juniper Creek, respectively (table 7, figure 13B). The area of recharge estimated for each headwater covers a broad upland are. In contrast, the recharge extent calculated for a downstream location of Turkey Creek was only about 2,409 ft from the sampling site and limited to a narrow extent on either side of the creek (figure 13B). As was the case for the downstream site of Toms Creek, it is not known which side of the creek the groundwater sample was ultimately derived from, so both sides are shown.

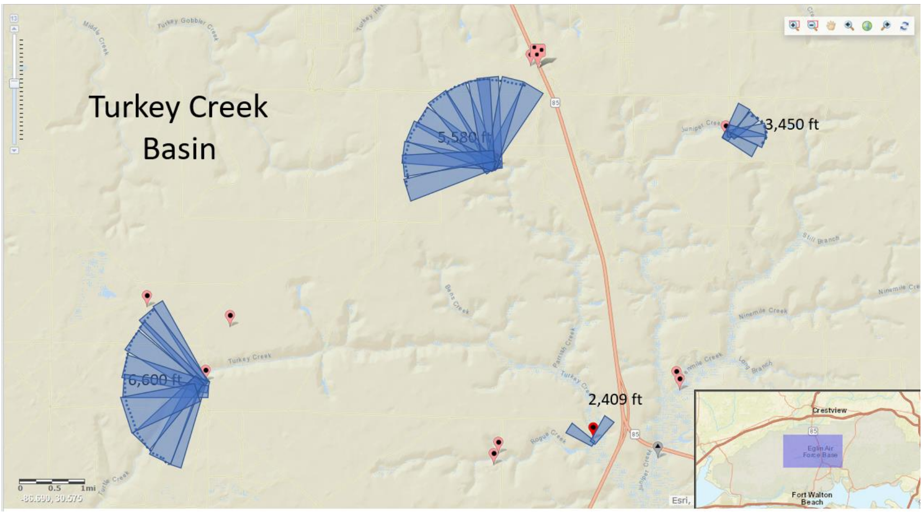


Figure 13B. The recharge extent for the headwaters of Turkey Creek basin was calculated to be approximately 4,180 ft for Turkey Creek, about 5,580 ft for Parrish Creek, and approximately 3,450 ft for Juniper Creek (table 7). The area of recharge estimated for each headwater covers a broad upland are. In contrast, the recharge extent calculated for a downstream location of Turkey Creek was only approximately 2,409 ft from the sampling site and limited to a narrow extent on either side of the creek, February and December 2020, Eglin Air Force Base, near Niceville, FL.

The recharge extent for the headwaters of Rocky Creek basin was calculated to be approximately 3,670 ft for Exline Creek, approximately 2,350 ft for Rocky Creek, and approximately 3,590 ft for Bully Horselot Branch (table 7, figures 13C, 13D, and 13E, respectively). The area of recharge estimated for each headwater covers a broad upland area. In contrast, the recharge extent calculated for a downstream location of East Rocky Creek Turkey at HWY 201 was only about 1,825 ft from the sampling site and limited to a narrow extent on either side of the creek (figure 13F).

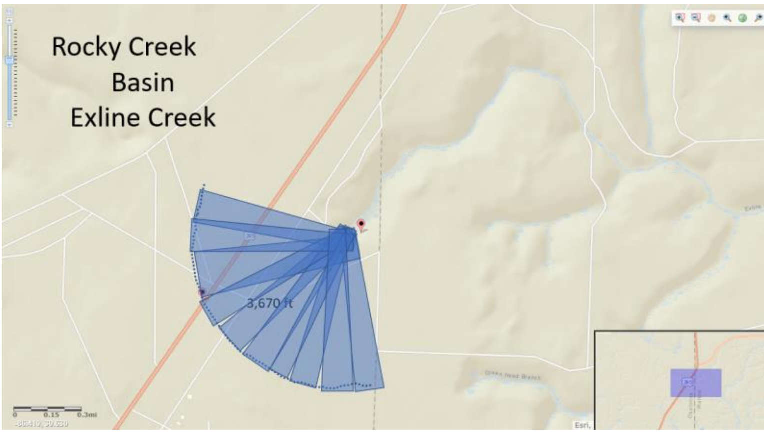


Figure 13C. The recharge extent for the headwaters of Rocky Creek basin was calculated to be approximately 3,670 ft for Exline Creek (table 7). The area of recharge estimated for the headwater covers a broad upland area.

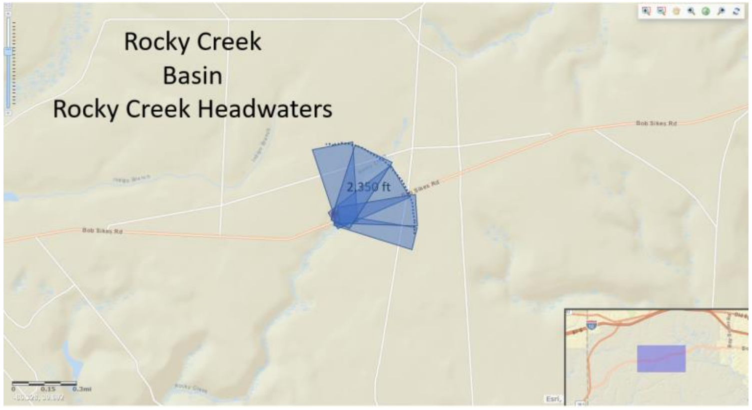


Figure 13D. The recharge extent for the headwaters of Rocky Creek basin was calculated to be approximately 2,350 ft for Rocky Creek (table 7). The area of recharge estimated for the headwater covers a broad upland area.

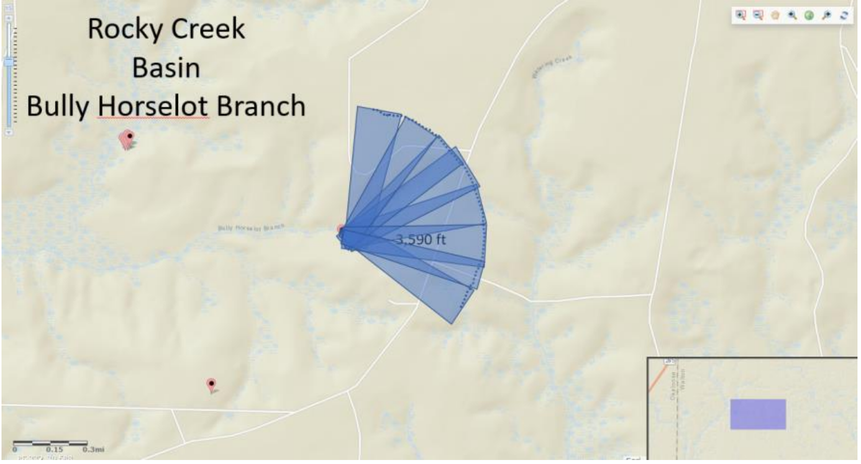


Figure 13E. The recharge extent for the headwaters of Rocky Creek basin was calculated to be approximately 3,590 ft for Bully Horselot Branch (table 7). The area of recharge estimated for the headwater covers a broad upland area.

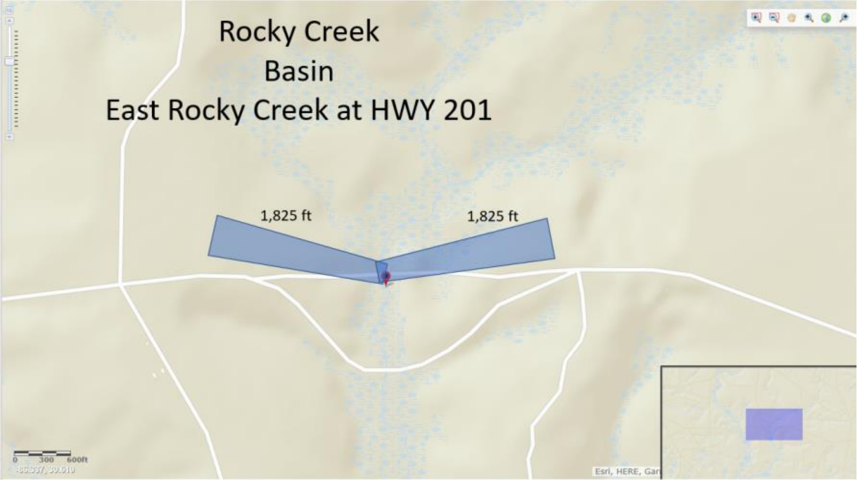


Figure 13F. The recharge extent for a downstream part of Rocky Creek basin (East Rocky Creek at HWY 201) was only about 1,825 ft from the sampling site and limited to a narrow extent on either side of the creek.

The recharge extent for a site near the headwaters of Swift Creek basin was calculated to be approximately 4,600 ft (table 7, figure 13G) and, as the site was not located at the headwaters, the recharge extents is limited to a narrow extent on either side of the creek, much like those sites sampled downstream in other basins. Moreover, the recharge extent calculated for a downstream location of Swift Creek at HWY 285 was almost as long, at approximately 3,825 ft and limited to a narrow extent on either side of the creek (figure 13H). This recharge extent for this downstream site is longer than the extents for previous downstream sites, perhaps because those were located in more natural areas and this site is located in a more urbanized area. Moreover, the recharge extents are located off the Eglin AFB property.

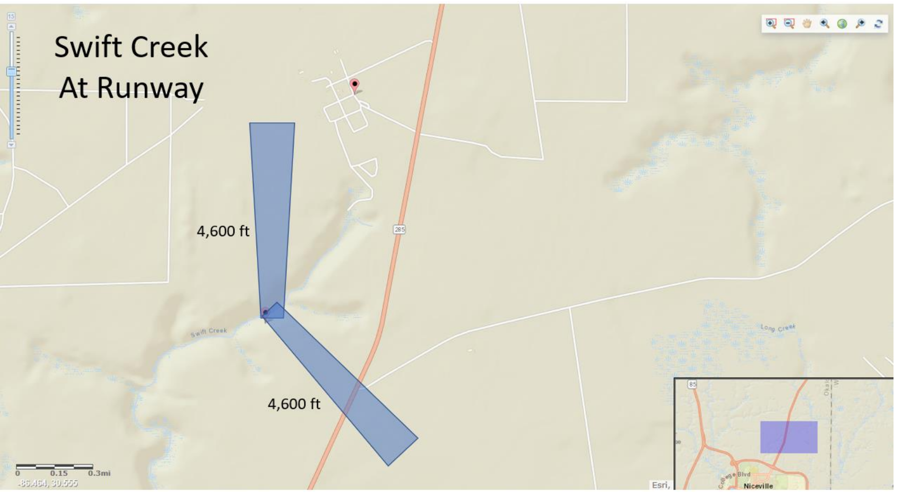


Figure 13G. The recharge extent for a site near the headwaters of Swift Creek basin was calculated to be about 4,600 ft (table 7) and, as the site was not located at the headwaters, the recharge extents is limited to a narrow extent on either side of the creek.

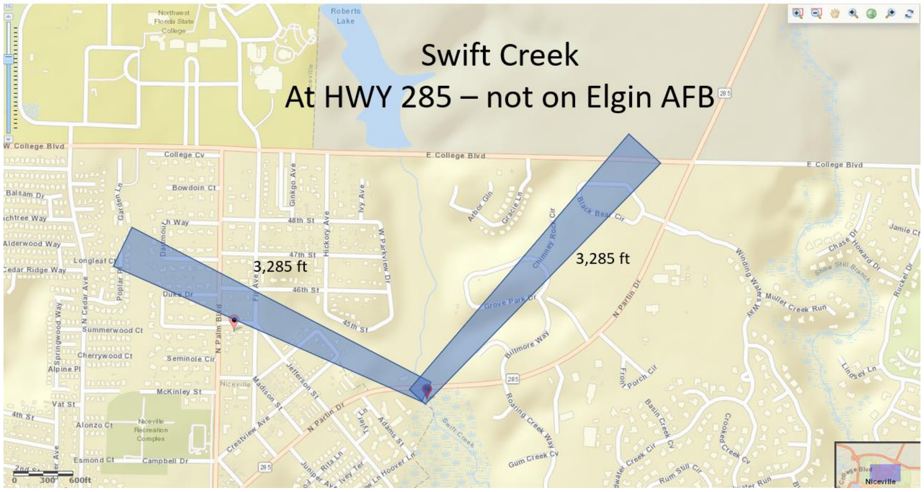


Figure 13H. The recharge extent calculated for a downstream location of Swift Creek at HWY 285 was approximately 3,825 ft and limited to a narrow extent on either side of the creek.

The recharge extent for the two headwater sites of Deer Moss Creek were calculated to be approximately 2,131 ft and 1,693 ft for the headwaters and SWB1, respectively (table 7, figures 13I). The recharge extent for the headwater site covers a large area, whereas the site at SWB1 has recharge extents of narrow areas on either side of the creek. The recharge extent calculated for a downstream location of Deer Moss Creek at Midbay connector was longer than for both headwater sites, at approximately 3,358 ft and limited to a narrow extent on either side of the creek Figure 13J). This long recharge extent for a downstream site may be since this site is located in a more urbanized area.

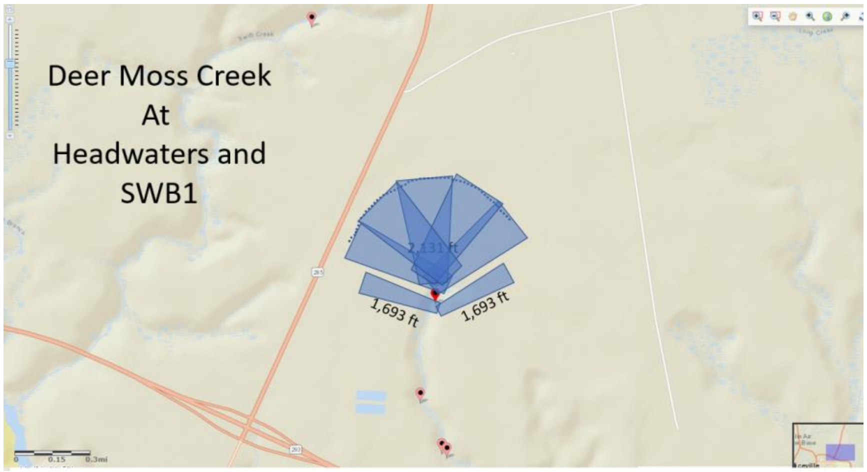


Figure 13I. The recharge extent for the two headwater sites of Deer Moss Creek were calculated to be approximately 2,131 ft and 1,693 ft for the headwaters and SWB1, respectively (table 7).

The recharge extent for the headwater site covers a large area, whereas the site at SWB1 has recharge extents of narrow areas on either side of the creek. The recharge extent calculated for a downstream location of Deer Moss Creek at Midbay connector was longer than for both headwater sites, at approximately 3,358 ft and limited to a narrow extent on either side of the creek. This long recharge extent for a downstream site may be since this site is located in a more urbanized area.

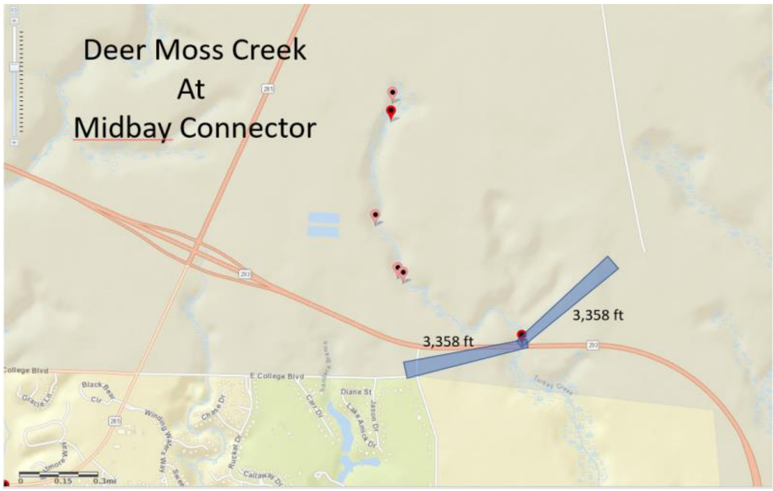


Figure 13J. The recharge extent calculated for a downstream location of Deer Moss Creek at Midbay connector was approximately 3,358 ft and limited to a narrow extent on either side of the creek.

The recharge extent for a site near the headwaters of Mill Creek basin was calculated to be approximately 1,971 ft (table 7, figure 13K). The recharge extent calculated for a downstream location of Mill Creek at West College Blvd was almost 2 times as long, at approximately 3,650 ft and limited to a narrow extent on either side of the creek. This recharge extent for this downstream site is longer than the extents for previous downstream sites, perhaps because those were in more natural areas and this site is located in a more urbanized area.

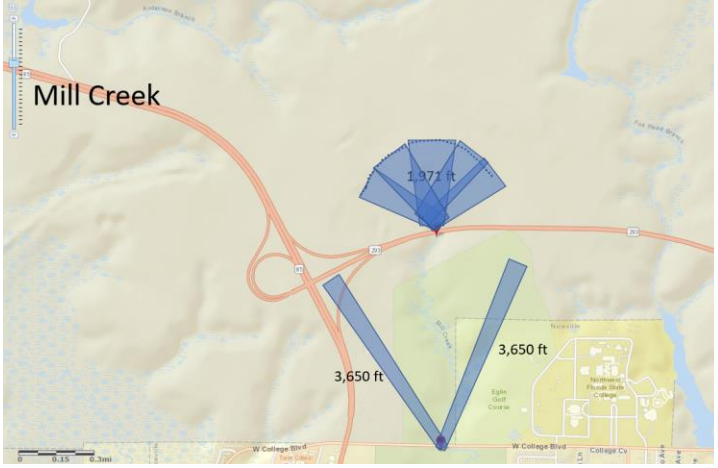


Figure 13K. The recharge extent calculated for a downstream location of Mill Creek at West College Blvd was about 3,650 ft and limited to a narrow extent on either side of the creek.

Management Implications

This study shows that the residence time of groundwater that supports flow in darter creeks is between 5 and 28 years. This timeframe between recharge in upland areas and discharge to creeks means resource managers should potentially shift the timeframes for longer duration monitoring and anticipated outcomes for management activities. For example, darter populations near headwaters of most of the creek basins characterized by natural areas may be less vulnerable to potential land-use changes or chronic or acute hazardous waste releases than darter populations located farther downstream or in areas characterized by urban land uses. This is because the headwaters of most creek basins, such as Toms Creek, Turkey Creek, and Rock Creek are characterized by older groundwater (greater than 16 years old) that recharged farther away from the creeks and, therefore, the longer groundwater flow time permits natural attenuation processes to act on decreasing contaminants prior to discharge. In contrast, darter populations near the headwaters of more urban basins, such as Mill Creek, Swift Creek, and Deer Moss Creek may be more vulnerable to potential land-use changes, chronic or acute hazardous waste releases, or increased sprayfield irrigation. At these basins, not only are the groundwater flow pathways shorter, and less time is available for natural attenuations processes to decrease contamination, the headwaters are facing water-quality challenges at the time of this study. In contrast to the more natural flow systems of Toms, Turkey, and Rocky Creek basins, the more urbanized basins of Mill Creek, Swift Creek, and Deer Moss Creek had the oldest groundwater detected at sites located farther downstream. A possible explanation may be that increases in percent impervious areas due to road and parking lots may decrease the rate of more recent recharge, and the groundwater is biased toward older groundwater recharged prior to these changes. Overall, this new information can be used by natural resource managers to support the USFWS Recovery Plan and proposed delisting of the Okaloosa darter from the Endangered Species List.

Benefits to the Military

This project was developed and funded to address a specific recovery criterion for the Okaloosa darter on Eglin AFB. In doing so, the results of this study are currently being used to improve management for the species and will ultimately be an essential component in the USFWS decision to remove the species from the Endangered Species List. While delisting a species is a massive achievement for the Department of Defense, particularly at the installation level, the findings of this study are broadly applicable across a large number of coastal installations and bases sited in areas of predominately well-drained, sandy soils. All bases are subject to Clean Water Act compliance and information on groundwater transport is essential to managing, mitigating, and offsetting impacts to surface waters that might compromise the military mission. Contaminant leeching from testing, training, or other mission activities as well as stormwater and wastewater controls are potential sources of groundwater impacts and are common to all military installations. Thus, avoidance measures are key components for mission planners and this project addresses both spatial and temporal considerations for range and base planning. Mapping recharge areas and predicting groundwater residence time and movement allow managers to predict not only where an action or impact might affect surface waters but also when. Mission flexibility is achieved by providing managers, planners, and regulators information essential to effective planning, protection, and restoration of critical natural resources on base.

Acknowledgements

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