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Determination of Recharge Areas That Supply Decades Old Groundwater to Creeks Inhabited by the Threatened Okaloosa Darter

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Abstract: The Okaloosa darter (*Etheostoma okaloosae*) is a diminutive, perch-like, benthic fish that inhabits only six small, clear, and shallow creek systems that flow almost entirely within Eglin Air Force Base in the panhandle of northwest Florida. Listed as Endangered by the U.S. Fish and Wildlife Service (USFWS) in 1973, improvements in erosion control and habitat restoration led to the Okaloosa darter being downlisted from Endangered to Threatened in 2011. However, the long-term management of the species is hampered by the lack of knowledge of the spatial extent of the recharge areas that ultimately support creek flow through groundwater discharge. To address this lack of data, we collected groundwater samples from the sand and gravel aquifer beneath 11 headwater and 11 downgradient sites across six creek basins during February and December 2020. The groundwater samples were collected from 1 to 1.2 m beneath the creek bottom. Concentrations of sulfur hexafluoride (SF_6) were analyzed and used to calculate groundwater age (residence time), and indicated that at the 11 headwater sites, recharge occurred between 11 and 28 years ago. Groundwater ages in downgradient parts of the same creeks indicated that recharge occurred between 5 and 25 years ago. When combined with representative values of hydraulic conductivity for the sand and gravel aquifer, the ages reveal that the extent of the maximum recharge distance from the sampling sites ranged from about 222 to 2011 m from 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 useful to fisheries biologists to incorporate groundwater inputs to facilitate fisheries management.

Keywords: Okaloosa darter; groundwater; Florida; recharge; groundwater age; endangered species

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1. Introduction

The Okaloosa darter (*Etheostoma okaloosae*) is a small (<4.9 cm), perch-like, benthic fish (Figure 1, inset) that inhabit only six small (1 to 9 m 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 1). In 1973, the species was listed as Endangered by the U.S. Fish and Wildlife Service (USFWS) due to the smothering of the creek habitat by eroded sediments 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 (Figure 1, long-term sampling locations) [1,2]. This information was used successfully to protect existing habitats and to restore imperiled habitats through the correction of erosion, contouring roadways, and planting vegetation in upland areas [3]. Success was facilitated by management by the Jackson Guard Natural Resources Division of Eglin AFB. As a result of these efforts, the Okaloosa darter was downlisted from Endangered to Threatened in 2011 [4].

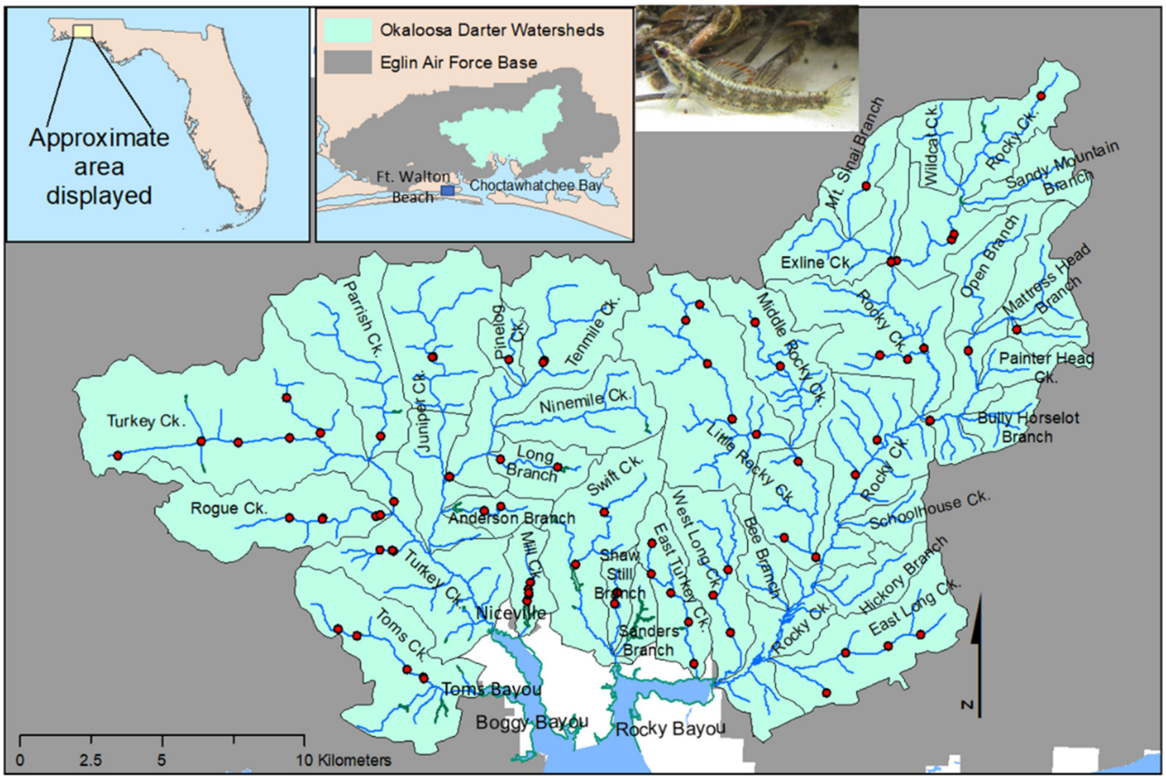


Figure 1. The study area with basins and creeks (blue lines) that contain Okaloosa darters (inset, upper right, darter resting on outcropping sand of the upper part of the sand and gravel aquifer), Eglin Air Force Base, northwestern Florida. Red-filled circles are long-term sampling locations used by the U.S. Fish and Wildlife Service to monitor darter populations over time. Surface-water boundaries are shown as black lines. [Photograph by William B. Tate, U.S. Fish & Wildlife Service].

Groundwater discharge from the regionally extensive sand and gravel aquifer is recognized as the primary source of flow in the darter creeks [5]. Few data, however, have been collected on the extent and location of recharge areas that provide this groundwater discharge. The long-term management of the species, including potential delisting from the Endangered Species List, would necessarily require such crucial information to meet the Recovery Objectives. These Objectives, defined by the USFWS as the reversal or arrest of a decline of an endangered or threatened species, include the assurance that natural, historical flow regimes are maintained, and stream habitat, water quality, and water quantity are protected [5]. The delineation of the extent of recharge would also provide new data for the long-term management of other threatened species, like the reticulated flatwoods salamander (*Ambystoma bishopi*).

The elucidation of recharge extent to the creeks would help answer questions such as: "Is there a difference in residence time (flow time) for groundwater that supports flow in headwater locations compared to sites located farther downstream?" and "How much time would be needed to remove any land-applied contaminants that entered groundwater before they would arrive at the creeks, or the potential for the contamination to be attenuated prior to discharge?". Moreover, such new information is imperative if future population or industrial growth are supported by new groundwater withdrawals from the sand and gravel aquifer that feeds these creeks.

To address this lack of data, we collected groundwater samples from the upper part of the sand and gravel aquifer that crops out beneath 11 headwater and 11 downgradient sites across six creek basins during February and December 2020. Age dates for the sampled groundwater indicated that at the 11 headwater sites, recharge occurred between 11 and 28 years before the date of sample collection. Groundwater ages in downgradient parts of the same creeks indicated that recharge occurred between 5 and 25 years before the date of sample collection. The fact that the creek flow observed today is supported by groundwater recharged up to decades ago is enlightening, and revealed that recharge can occur more than 1.6 km away from a particular creek headwater.

2. 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 1). The creeks flow almost entirely within Eglin AFB, one of the world's largest conventional weapons testing facilities.

2.1. Climate

The climate is generally humid and subtropical, with warm summers and mild winters. The average summer temperature is 81 degrees Fahrenheit (°F) (27 degrees Celsius (°C)), and the average winter temperature is 54 °F (12 °C). At Niceville, FL, the annual average precipitation from 1931 to 1978 was 157 cm [6]. Higher precipitation amounts are observed during the summer months and lower amounts during the winter.

2.2. Physiography

The study area is in the Gulf Coastal Plain physiographic province. The area is characterized by a transition from deeper limestones that dominate the Floridian 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*).

The topographic relief of the sandhills is greater than for most of Florida, and is driven by the erosion of these sandhills caused by both surface water and groundwater. Drainage on the western part of Eglin AFB is characterized by a unique east–west trellis pattern (Figure 1). This pattern was most likely created by headward erosion by groundwater sapping [7] and has been seen at other high altitude, well drained, coastal plain sediments in the Gulf Atlantic coastal plain [8]. The 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 of Eglin AFB is a classic north–south dendritic pattern caused by surface-water erosion and has headwaters furthest inland. The latter drainage pattern is what would be expected in a terrain dominated by well-drained unconsolidated sand.

2.3. Hydrogeology

In general, the study area is underlain to depths of 76 m 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 (Figure 2) [9]. 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 [10] 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 groundwater for human consumption tap the Upper Floridan.

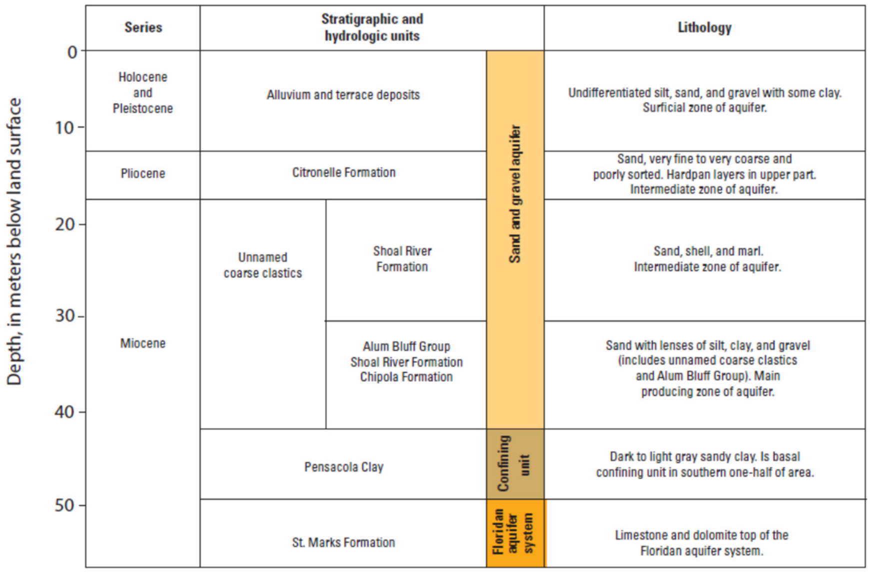


Figure 2. Generalized stratigraphic column from a representative core hole near Fort Walton Beach, near the study area at Eglin Air Force Base, Niceville, Florida (Adapted from [10]).

Specifically of relevance to this study, the sand and gravel aquifer covers all of 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 2). In general, the sand and gravel aquifer comprise three zones based on differences in lithology and hydraulic properties: the surficial (water table, 0–15 m bls), intermediate (lower permeability, 18–38 m bls), and main-producing (38–64 m bls) zones. The aquifer can reach a thickness up to 61 m bls in southwestern Okaloosa County [10]. 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. Overland flow is minimal and only contributes to streamflow after heavy precipitation events due to the porous nature of the surficial aquifer.

2.4. Creek Flow

Groundwater from the upper part of the sand and gravel aquifer has long been recognized as the primary source of water that flows in the darter creeks [5]. 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 a source of flow groundwater from much deeper limestones of Miocene or older age. Regardless of the ultimate source of groundwater to surface-water systems, groundwater is crucial to sustaining surface-water flow and its associated ecosystems at many surface-water bodies in Florida and elsewhere around the globe (see review paper [11]).

The six creeks studied include Toms, Turkey, Mill, Swift, Deer Moss (formerly called East Turkey), and Rocky Creeks (Figure 1). The total drainage of the six creeks is 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), for Juniper Creek is 89 cfs, based on 34 years of records (USGS Site ID 02367310) (https://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=02367310 (accessed on 26 January 2022)). 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 the stream flow. Short-term, transient, and rapidly dissipated peaks in discharge are due to the direct addition of seasonal-driven, higher amounts of precipitation [12]. Even though the summer months are characterized by higher amounts of precipitation (e.g., the month of July can have up to 20 cm of precipitation), discharge is often at its lowest because the infiltrated groundwater is rapidly removed by evaporation and transpiration (ET) before the groundwater reaches the creeks.

3. Methods

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

3.1. Study Design

Flow in creeks inhabited by the Okaloosa darter is derived from groundwater, starting as the infiltration of local precipitation to the water table, or recharge, and was indirectly recognized as early as the late 1990s [5]. To determine where it entered as recharge, we used an approach that involved the collection of groundwater samples from the sand and gravel aquifer beneath the creeks at headwater and downstream locations of each creek basin.

3.2. Creek Basins Studied and Sites Sampled

A brief description of each basin shown in Figure 1 is provided here; additional information can be found in [3]. The sampling sites used in this study are shown in Figure 3.

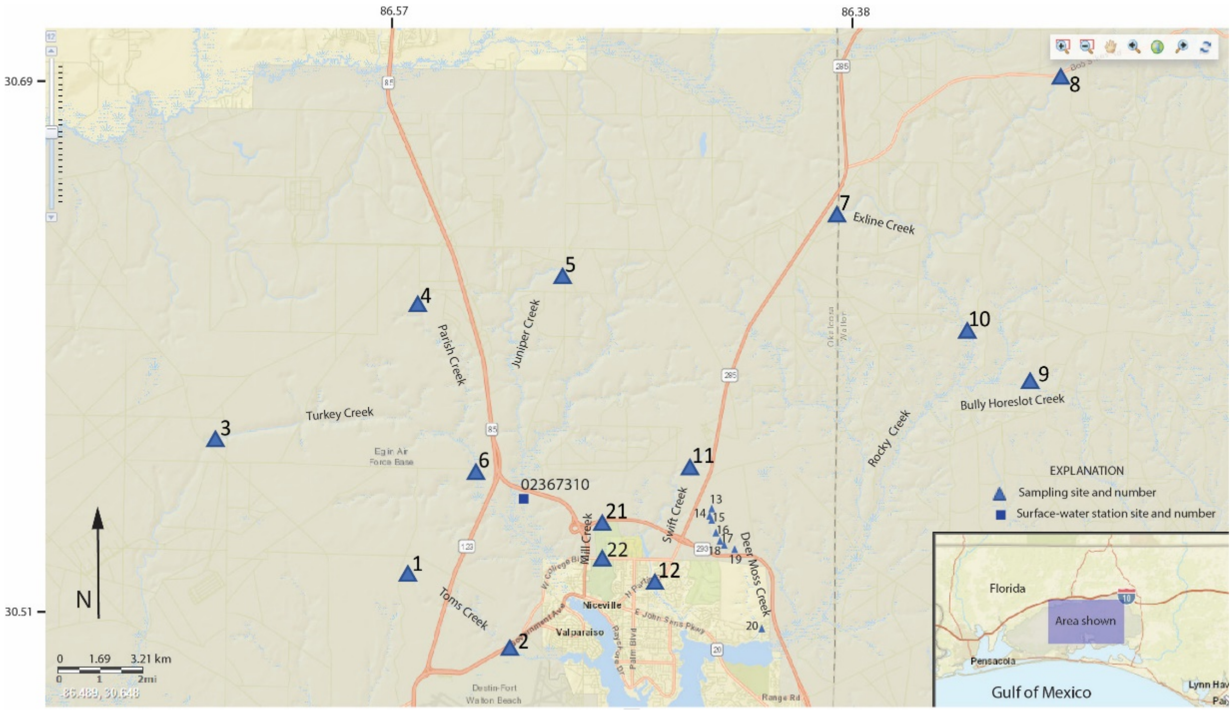


Figure 3. Groundwater sampling sites at Eglin Air Force Base, near Niceville, Florida, for Toms Creek, Turkey Creek, Mill Creek, Rocky Creek, Swift Creek, and Deer Moss Creek basins, February and December 2020. The numbers refer to sample location names discussed below and in Table 1. Also shown is the location of USGS monitoring station 02367310 on Juniper Creek) (Base map: USGS National Water Information System Mapper).

Table 1. Groundwater sample location name and number, U.S. Geological Survey (USGS) station name, and latitude and longitude, Eglin Air Force Base and surrounding area near Niceville, Florida. **Number in parentheses after location name is site number; only site number is shown in Tables 2–7.**

Sample Basin, Name, and Number (Figure 3)	USGS Station Name	Latitude	Longitude
Toms Creek Basin			
Toms Creek Headwaters (1)	303144086335800	30.528972	86.524167
Toms Creek at Eglin Parkway (2)	303023086312700	30.506444	86.524167
Turkey Creek Basin			
Turkey Creek Headwaters (3)	303429086381400	30.574639	86.637278
Parish Creek Headwaters (4)	303722086334200	30.622667	86.561583
Juniper Creek Headwaters (5)	303745086300700	30.629194	86.501833
Turkey Creek, Range Road 232 (6)	303342086321000	30.561667	86.536111
Rocky Creek Basin			
Exline Creek Headwaters (7)	303837086233500	30.643528	86.392944
Rocky Creek Headwaters (8)	304140086180600	30.694333	86.301611
Bully Horselot Headwaters (9)	303537086183200	30.593528	86.308972
East Rocky Branch Creek Highway 201 (10)	303656086193500	30.615500	86.326497
Swift Creek Basin			
Swift Creek South of Runway (11)	303354086270000	30.565083	86.450083
Swift Creek at Highway 285 (12)	303141086280000	30.527997	86.466800
Deer Moss Creek Basin			
Deer Moss Headwaters (13)	303300086263000	30.549944	86.441583
Deer Moss Headwaters Near SWB1 [a] (14)	303256086263000	30.548917	86.441667
Deer Moss, at SWB1 [a] (15)	303256086263000	30.548917	86.441667
Deer Moss, at SWB2 [a] (16)	303235086263400	30.587197	86.561300
Deer Moss, at SWB3 [a] (17)	303225086262800	30.409400	86.473800
Deer Moss, at SWB4 [a] (18)	303224086262700	30.539900	86.440900
Deer Moss, at MidBay Connector (19)	303211086260000	30.536400	86.433200
Deer Moss, at Rocky Bayou Drive (20)	303045086253100	30.512500	86.425000
Mill Creek Basin			
Mill Creek, headwater (21)	303251086291100	30.547500	86.486301
Mill Creek, at West College Blvd (22)	303206086291000	30.535000	86.486000

[a] SWB*n*, Surface Water sampling location identifier and number, B*n*.

Toms Creek Basin. Toms Creek drains into Toms Bayou (Figure 1). It is the third largest basin at 20.7 km^2. The headwaters are relatively undeveloped, with beaver dams and ponds in downstream reaches. The samples for this study were collected near the headwaters (Site 1) and downstream side of a bridge of highway (HWY) 85 (Site 2) (Figure 3).

Turkey Creek Basin. Turkey Creek, Parish Creek, and Juniper Creek drain into Boggy Bayou (Figure 1). Most of the basin is undeveloped as it is located on Eglin AFB. The samples were collected at each headwater (Sites 3, 4, and 5), and at Range Road 232 where it crosses Turkey Creek (Site 6) (Figure 3).

Rocky Creek Basin. Rocky Creek, Exline Creek, and Bully Horselot Creek drain into Rocky Bayou (Figure 1). Most of the basin is undeveloped as it is located on Eglin AFB. The samples were collected at each headwater (Sites 7, 8, and 9), and at East Rocky Branch Creek at HWY 201 (Site 10) (Figure 3).

Swift Creek Basin. Swift Creek drains into Rocky Bayou (Figure 1). 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 Boulevard (Blvd) before flowing through an urban area and emptying into Rocky Bayou. The samples were collected at the headwater (Site 11) and at HWY 285 (Site 12) (Figure 3).

Deer Moss Basin. Deer Moss Creek (also known locally as Turkey Bolton Creek) drains into Rocky Bayou (Figure 1). Wastewater treatment by sprayfield irrigation occurs on the plateaus on each side of the creek. The sprayfields were constructed in 1982, and between

4.5 to 9 million liters per day (ML/d) of treated wastewater are applied at land surface (William Tate, U.S. Fish & Wildlife Service, written commun., 2021). The samples for this study were collected near the headwaters (Sites 13 and 14), upstream (Sites 15 and 16) and downstream (Sites 17 and 18) of the sprayfield, adjacent to HWY 293 (Site 19) and the downstream side of a bridge on Rocky Bayou Dr. (Site 20) (Figure 3).

Mill Creek Basin. Mill Creek drains into Boggy Bayou (Figure 1). It is one of the smallest drainages inhabited by Okaloosa darters at 4.6 km^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 Boggy Bayou (Figure 1). Significant creek restoration activities have occurred within the golf course areas [3]. The samples for this study were collected near the headwaters adjacent to HWY 293 (Site 21) and downstream side of a bridge on West College Blvd (Site 22) (Figure 3).

The sites sampled in February and December 2020 are shown in Figure 3. The samples were collected from the upper part of the sand and gravel aquifer below 11 headwater and 11 downgradient sites across the six creek basins. Each numbered site was named using a unique USGS station identifier and entered into the USGS National Water Information System database [13] (Table 1). Initial groundwater samples were collected during February, but travel restrictions delayed additional sample collection until December 2020. Fortunately, both sampling events occurred during the fall/winter, when precipitation amounts are lower, so the samples were not affected by precipitation or runoff. Although flow was not measured during sampling, contemporaneous stream gage height and discharge measurements made at a continuous, real-time station (USGS monitoring station 02367310; Figure 3) were used to support the timing of the sample collection. 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.

3.3. Groundwater Head Measurements

The altitude that groundwater rose above the altitude of a particular creek sampling site was measured using a 'temporary well' and tape measure. The temporary well comprised a 6.35 mm bore, stainless steel pipe that had mill-slot screens, and a point on the bottom end, also known as a 'drivepoint' or 'push-point sampler" (DeepWater2 PushPoint Sampler, MHE Products). At each sampling site in the creek, a solid rod was first inserted down the stainless steel pipe before deployment, and this temporary well was manually advanced such that the screen was approximately 1 to 1.2 m below the creek bottom; this depth interval was selected to ensure that the samples were reflective of upwelling groundwater from the upper part of the sand and gravel aquifer, rather than a mixture of groundwater and surface water in the hyporheic zone directly beneath the creek [11,14]. The solid 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 the groundwater rose above the surface-water level, or head, was recorded (Figure 4). To ensure that the head measurements would be comparable across all sites, the temporary well was inserted through the same depth of surface water, which was about 15 cm.

3.4. Groundwater and Creek Geochemistry Measurements

Water-quality parameters were measured in the field for groundwater pumped from the temporary wells. At the same time, these parameters were also measured in surface water. Water samples were also collected for laboratory analyses.

Figure 4. The altitude that groundwater rises above the surface-water level can be seen in the clear tubing (in this case, about 12 cm of positive head difference) attached to the temporary well pushed 1 to 1.2 m below the creek bed into the upper part of the sand and gravel aquifer. Observation of groundwater rising above the surface water level provided unequivocal evidence that a particular sampling site was characterized by groundwater discharge (i.e., a vertical upward gradient, or gaining stream). [Photograph by James E. Landmeyer, U.S. Geological Survey].

3.4.1. Field Measurements

Measurements of the physical properties and chemical constituents of groundwater and surface water, such as dissolved oxygen, pH, specific conductance, and temperature, were measured using two Aqua TROLL 600 Multiparameter Sondes (In-Situ, Inc., Fort Collins, CO, USA). Each 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 [15]. The parameters were measured in groundwater pumped from the temporary well using a peristaltic pump at low-flow rates and into a nylon graduated cylinder where the sonde was placed (the natural flow rate from the temporary well precluded sample collection in a timely manner). Groundwater samples were collected after the measurements of dissolved oxygen, pH, specific conductance, and temperature, as shown by the sonde, had stabilized (Figure 5). The groundwater did not require filtration because of low to zero sample turbidity. Samples of surface water were collected using the same method. Measurements of the physical properties and chemical constituents of the surface water were made using the same method, but by placing the second sonde in the creek water column near the bottom; in all sampling sites, the depth of the surface-water column was about 15 cm.

3.4.2. 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 sampled groundwater first recharged the water table (in other words, the water was removed from contact with the atmosphere) using the methods described by Busenberg and Plummer [16] and using the assumption of a piston-type flow [17]. The piston-type flow model conceptualizes groundwater flow as a 'unit volume' 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 [17].

Figure 5. Upwelling groundwater from 1 to 1.2 m below the creek in the upper part of the sand and gravel aquifer was sampled using a peristaltic pump (yellow case) attached to the temporary well (foreground). A 6.35 mm inner diameter 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. [Photograph by James E. Landmeyer, U.S. Geological Survey].

Groundwater can be dated with SF_6 (±5 years) 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 [16]. 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 the chlorofluorocarbons (CFCs), also used to date groundwater, the air-concentration curve is increasing, making SF_6 especially rigorous for dating groundwater younger than the mid-1990s.

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 L amber glass bottles) were filled from the bottom and allowed to overflow. The sample tubing was made of vitex or copper to eliminate the 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 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 (Shimadzu GC-8A with an electron-capture detector and custom inlet system). The range of possible solutions for recharge extent was compared to piston-flow model recharge ages using TracerLPM [18], an interactive Excel-workbook program used to evaluate groundwater-age distributions.

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 [19], 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 (125 mL glass vials) were filled beneath a volume of groundwater pumped from the monitoring well into a 2 L graduated nylon cylinder (Figure 5). The sample tubing, made of vitex or copper to eliminate the 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 was 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 L 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, Virginia, where the dissolved gas analyses were completed in duplicate using chromatograph/flame ionization detection (Hewlett Packard 7890B GC, with a thermal conductivity detector and a flame ionization detector).

Groundwater and surface water often have unique stable isotope values for hydrogen (H) and oxygen (O) because when surface water is exposed to the air, the lighter isotopes preferentially evaporate and render the remaining water enriched in the heavier isotopes. In contrast, groundwater tends to retain the values characteristic of the water upon recharge. Groundwater samples for the stable isotope analyses of hydrogen (as delta H, or δ^2H) and oxygen (as delta O, or δ^{18}O) 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, Virginia, and the stable isotopes quantified using dual-inlet isotope-ratio mass spectrometry (VG Micromass 602 and Los Gatos Research DLT-100). The values for each sample were compared to each other to understand relative differences between the sample locations. The values also were compared to a local meteoric water line [20] and the global meteoric water line [21].

3.5. Recharge Extent and Area Determinations

The measured SF_6 concentration and, therefore, age date (time of recharge before sample collection) was used to estimate the distance, or extent, from each creek sampling site, where this distance equates to the probable maximum distance from the creek where recharge would have occurred to result in that particular groundwater age. The relation between groundwater age and recharge distance is given as follows:

$$L = VT \quad (1)$$

where L is the recharge extent (m), V is the velocity of groundwater flow (m per day (m/d)), and T is the time since recharge, or groundwater age (d). Darcy's Law was used to solve for V by calculating the seepage velocity of groundwater, v, as follows:

$$v = iK/n \quad (2)$$

where i is the hydraulic gradient between groundwater in upland areas (the generalized potentiometric surface from Hayes and Barr [10] was used because more recent data are not available), K is the hydraulic conductivity (m/day) of the surficial aquifer, where K was calculated using the following:

$$K = T/b \quad (3)$$

where b is the thickness of the aquifer (m) from Hayes and Barr [10], T is transmissivity (m^2/d), also from Hayes and Barr [10] was used because no additional work has been done to expand that dataset, and n is the aquifer porosity (unitless). From this, the recharge distance, L (Equation (1)), for each groundwater age date at each sampling site was calculated using the best possible hydrogeologic data.

The recharge extents were calculated using hydraulic conductivity (K) values of 15, 30, and 38 m/day. This range of values is characteristic of the upper part of the sand and gravel aquifer and using a range of values rather than a single value addresses the uncertainty surrounding the lack of knowledge of the actual K values of the surficial zone of the sand and gravel aquifer in the study area. The recharge extents calculated using these three K values help to provide acceptable travel distances for 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. As such, the calculated recharge extent is the maximum probable distance from the creek sampling site that the sampled groundwater discharge below the creek could have entered as recharge at a known time in the past. However, it is important to keep in mind that groundwater can still be recharged along the entire groundwater flow pathway.

After the recharge distance from each sampling site was calculated, the land-surface expression of the recharge extent (area) for headwater and downstream sites was qualitatively mapped using the calculated recharge extent and concept of flow-net analysis [22]. Groundwater flow pathways start in the calculated maximum recharge extent and stop in the discharge area of the creek. Flow pathways originate across a broader area for the headwater sites and, conversely, originate in more defined areas on either side of the creek for the downstream sites, following the fundamentals of flow-net analysis [22].

4. Results

4.1. Creek Flow

Stream discharge measurements recorded during February and December 2020 at the Juniper Creek site (USGS monitoring station 02367310) (Figure 3) confirmed that the sampling events were not influenced by overland flow following recent precipitation (Figure 6). The median streamflow was about 70 cfs from 1 January 2020 to 1 September 2020. Thereafter, the median streamflow until 1 January 2021 was about 90 cfs. Discharge was higher during the fall and winter of 2020, most likely due to less interception of groundwater on account of seasonally lower ET rates (Figure 6).

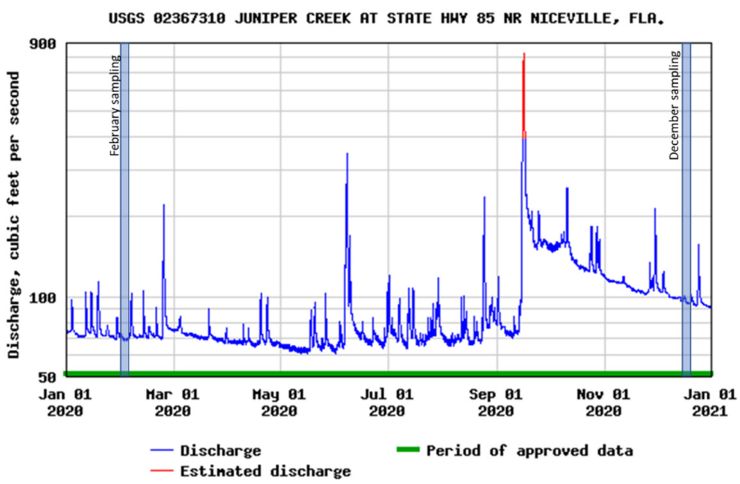


Figure 6. Discharge, in cubic feet per second, measured at Juniper Creek (USGS monitoring station 02367310) during 2020. The two field-sampling events described in this report are shown.

4.2. Groundwater Head Measurements

All 22 sites had groundwater head measurements in the upper part of the sand and gravel aquifer beneath the creeks that were above the surface-water level (Table 2). These data indicate all sites are dominated by a vertical upward hydraulic gradient characteristic of a location of groundwater discharge. These novel head measurements provide the first data collected in the study area to support previous suggestions that the darter creeks are predominately supplied by groundwater from the sand and gravel aquifer [5,10,23].

Table 2. Groundwater sample location name and number, sample date and time, results of field measurements of head (cm) above altitude of creek water, and vertical upward hydraulic gradient, Eglin Air Force Base and surrounding area near Niceville, Florida, 4–6 February and 14–16 December 2020. Heads were measured in inches and converted to centimeters (cm). Refer to Table 1 for specific site location name of site number.

Sample Basin and Number (Figure 3)	Sample Date	Sample Time	Altitude, Groundwater Head above Creek Water Level (cm)	Hydraulic Gradient, Vertical, Upward (Dimensionless)
Toms Creek Basin				
1	4 February 2020	1130	8.89	0.08
2	4 February 2020	925	3.81	0.03
Turkey Creek Basin				
3	4 February 2020	1400	11.4	1.10
4	4 February 2020	1530	11.4	1.10
5	4 February 2020	1815	6.35	0.07
6	16 December 2020	811	1.27	0.01
Rocky Creek Basin				
7	5 February 2020	900	8.25	0.07
8	5 February 2020	1110	11.4	1.10
9	5 February 2020	1430	7.62	0.07
10	14 December 2020	1634	5.08	0.04
Swift Creek Basin				
11	5 February 2020	1630	24.1	0.22
12	15 December 2020	1446	8.89	0.08
Deer Moss Creek Basin				
13	6 February 2020	840	15.2	0.14
14	6 February 2020	1000	10.1	0.09
15	15 December 2020	1248	1.90	0.01
16	15 December 2020	1016	20.3	0.19
17	15 December 2020	1109	8.89	0.08
18	15 December 2020	1334	35.5	0.33
19	14 December 2020	1112	2.54	0.02
20	15 December 2020	840	12.7	0.11
Mill Creek Basin				
21	14 December 2020	841	1.27	0.01
22	15 December 2020	1526	3.81	0.03

The magnitude of groundwater head, as measured in the temporary wells above the surface water and resultant vertical upward hydraulic gradient, 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 a more intermediate flow regime (some natural flow and some artificially impacted flow), such as Swift Creek, the groundwater head and vertical gradients above the surface water were greater in the headwaters (Site 11) upstream of a dam (at East College Blvd) and lower at the downgradient (Site 12). The same scenario was observed in the sprayfield-impacted basin of Deer Moss Creek, where the groundwater head above the surface water was greater in the headwaters and lower in downgradient locations; however, the greatest groundwater head was measured in the middle reach (Site 18), due to the input of treated water from sprayfields located in the uplands on each bank. An in-depth study of the effect of the sprayfield leachate on the groundwater head, as well as groundwater and surface-water quality, was beyond the scope of the investigation. In contrast to these basins, the groundwater head and vertical gradient above the surface water was lower in the headwaters and higher in the downgradient location in the golf course-impacted basin of Mill Creek (Table 2).

4.3. Groundwater and Creek Geochemistry Measurements

4.3.1. Field Measurements

Dissolved Oxygen

In general, the groundwater upwelling to the headwaters of the six darter basins had higher concentrations of dissolved oxygen (DO) (1.37–9.24 mg/L, average = 4 mg/L) compared to the lower DO concentrations measured farther downstream (0.86–2.33 mg/L, average = 1 mg/L) (Table 3). Dissolved oxygen in the groundwater had entered during the recharge of oxygen-saturated (8.0 mg/L at 25 °C) precipitation. The measurement of DO near 8 mg/L in groundwater upwelling to creeks after some distance of transport underground indicates that little biological or mineral oxygen demand in the upper parts of the sand and gravel aquifer. In contrast, lower DO concentrations measured in groundwater indicate the presence of sinks for dissolved oxygen, such as respiration by aerobic heterotrophic bacteria in the aquifer formation material or the removal caused by mineral (e.g., Fe(II)) oxidation. In contrast, DO concentrations in the surface water were consistently greater than 7.90 mg/L at all 22 sites (Table 3), even where the DO in upwelling groundwater was observed to be much lower.

Table 3. Sample location name and number, sample date and time, and results of field measurements of temperature (°C, degrees Celsius), specific conductance (µS/cm, microsiemens per centimeter at 25 degrees Celsius), pH, and dissolved oxygen (DO)(mg/L, milligrams per liter), of groundwater (GW) and surface water (SW), Eglin Air Force Base and surrounding area near Niceville, Florida, 4–6 February and 14–16 December 2020. Refer to Table 1 for specific site location name of site number.

Sample Basin and Number (Figure 3)	Sample Date	Sample Time	GW or SW	Temperature (°C)	Specific Conductance (µS/cm)	pH	Dissolved Oxygen (mg/L)
Toms Creek Basin							
1	4 February 2020	1124	GW	21.09	16.42	5.18	8.47
		1130	SW	20.75	15.32	4.84	8.28
2	4 February 2020	925	GW	15.60	125.0	6.39	1.00
		815	SW	14.95	23.00	5.89	9.03
Turkey Creek Basin							
3	4 February 2020	1400	GW	21.02	12.89	5.03	8.61
		1400	SW	21.16	14.80	5.06	8.59
4	4 February 2020	1530	GW	20.76	16.11	5.00	8.64
		1533	SW	20.42	12.18	5.02	8.35
5	4 February 2020	1815	GW	20.41	14.72	4.88	6.60
		1815	SW	19.60	11.15	5.01	8.03
6	16 December 2020	850	GW	15.29	69.39	4.07	0.86
		811	SW	16.12	13.50	4.53	9.30
Rocky Creek Basin							
7	5 February 2020	915	GW	21.17	17.36	5.15	8.71
		853	SW	20.18	13.84	5.00	8.80
8	5 February 2020	1118	GW	20.17	16.34	4.81	2.64
		1100	SW	19.10	13.88	4.60	8.39
9	5 February 2020	1435	GW	19.38	14.82	5.06	9.24
		1415	SW	18.21	14.85	5.02	8.41
10	14 December 2020	1634	GW	17.73	50.95	5.60	1.97
		1634	SW	18.46	10.48	5.73	8.94

Table 3. *Cont.*

Sample Basin and Number (Figure 3)	Sample Date	Sample Time	GW or SW	Temperature (°C)	Specific Conductance (µS/cm)	pH	Dissolved Oxygen (mg/L)
11	5 February 2020	1630	GW	20.55	19.13	5.07	8.83
		1615	SW	20.42	18.50	5.81	8.39
12	15 December 2020	1446	GW	17.13	55.18	5.53	2.46
		1446	SW	17.06	27.50	6.18	9.18
Deer Moss Basin							
13	6 February 2020	845	GW	20.92	17.61	4.88	6.73
		835	SW	20.40	16.36	4.93	7.90
14	6 February 2020	955	GW	21.03	18.07	4.94	5.17
		945	SW	20.54	16.24	4.94	8.05
15	15 December 2020	1248	GW	19.10	20.78	5.07	6.52
		1248	SW	18.95	17.86	5.18	8.27
16	15 December 2020	1022	GW	18.93	468.0	5.56	7.84
		1016	SW	17.78	73.23	5.70	8.69
17	15 December 2020	1109	GW	18.63	252.0	5.88	7.04
		1111	SW	18.11	101.5	6.60	8.54
18	15 December 2020	1334	GW	19.97	28.64	5.48	3.38
		1334	SW	18.87	21.04	5.73	8.47
19	14 December 2020	1146	GW	18.94	60.11	5.24	1.12
		1112	SW	18.96	104.2	6.57	8.81
20	15 December 2020	853	GW	13.68	47.18	5.18	2.33
		840	SW	13.10	80.99	6.66	9.46
Mill Creek Basin							
21	14 December 2020	852	GW	17.82	18.22	3.94	1.37
		841	SW	18.29	21.38	4.34	7.76
22	15 December 2020	1526	GW	18.37	119.5	5.84	0.97
		1526	SW	17.30	39.05	6.18	8.55

Specific Conductance

In general, the specific conductance values in the groundwater were 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 that are characterized by little remaining solubility. There was a trend of increasing specific conductance in the groundwater from headwater sites (12.89–19.13 µS/cm, average = 15 µS/cm) to downstream sites (14.72–125 µS/cm, average = 90 µS/cm) (Table 3). This increase may reflect more input to groundwater from sources at land surface. The specific conductance of surface water decreased downstream in the Turkey Creek and Rocky Creek basins. The highest specific conductance in groundwater (468 µS/cm) was for Deer Moss Creek (Site 16), where the upwelling groundwater was impacted by groundwater that contained sprayfield leachate coming from both sides of the creek.

pH

The pH of the groundwater and streams was less than 7 and acidic (Table 3), and is characteristic of precipitation of much of the southeastern US [24]. The groundwater pH ranged from 3.94 to 6.39. The surface water pH ranged from 4.34 to 6.66. The groundwater pH was lower due to the little natural mineral buffering capacity of the aquifer and the input of carbon dioxide from the natural aerobic metabolism of organic matter and root respiration. In contrast, the surface water pH was slightly higher, as carbon dioxide volatilizes from the water surface to the atmosphere as the water flows downstream over a rough terrain.

In the Toms Creek, Swift Creek, and Mill Creek basins, the pH of the 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

(Site 21) was the lowest measured at any site. In the Deer Moss basin, the pH increased from lows at the headwater (Sites 13–15) to downstream sites (Table 3). The pH increased mid-reach (Sites 16–18) due to the input of infiltrated sprayfield leachate reaching the creek at these locations. These were some of the highest pH measurements measured in surface water, and the higher pH levels persisted downstream away from the direct interaction with sprayfield leachate.

Groundwater and Surface Water Temperature

The groundwater was slightly warmer than the 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 exposed at the land surface [11]. Higher temperatures were observed for both the 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 downstream Site 20 of Deer Moss basin.

4.3.2. Laboratory Analyses

SF_6 and Piston Flow Model Recharge Age

The concentrations of SF_6 in the groundwater beneath the creeks ranged from 0.95 to 3.28 fMol/L (femtomoles per liter) (Table 4). Higher concentrations are directly related to younger groundwater, and the ages of the upwelling groundwater ranged from 5 to 28.6 years before sample collection across all sites. As such, the piston flow model recharge ages computed using TracerLPM [18] ranged from as recent as 2016 (Site 10) to as old as mid-1991 (Site 1).

For Toms Creek, Turkey Creek, and Rocky Creek (the natural flow regimes), the headwater sites were characterized by older groundwater with younger groundwater discharge limited to the downstream sites (Table 4). In contrast, Mill Creek, Swift Creek, and Deer Moss Creek headwater sites were characterized by relatively younger water, with older groundwater in downstream sites. 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 land uses compared to the larger three basins. Specifically, the youngest recharge age of these three basins was 11.6 years and was observed at Site 15. This location is located downgradient from treated wastewater sprayfields located in the recharge area on both sides of the creek. Because the sprayfields were constructed and functioning in the early 1980s, this part of Deer Moss Creek has received this additional water for over 30 years. The implications of the distribution of groundwater ages in relation to recharge extent and darter management are discussed in the Discussion section.

Dissolved Gases

Methane was not detected in the groundwater at any of the headwater sites, with the single exception of a trace of methane in the groundwater at the headwaters of impacted Mill Creek (Site 21) (Table 5). Oxygen detection was the inverse of methane. The lack of methane and the presence of dissolved oxygen in these groundwater samples supports the oxic-rich groundwater measured at these headwater locations. In contrast, methane was detected at all downgradient locations, characterized by lower concentrations of dissolved oxygen (Table 5). The highest concentrations of carbon dioxide were detected in the groundwater at 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 headwater and downgradient sites and probably reflect the absorption of nitrogen gas from the atmosphere (78 percent) into the water at the 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 are shown in Table 5 and were used as part of the input to TracerLPM, as previously described.

Table 4. Sample location name and number, concentrations of sulfur hexafluoride (SF_6) (in femtomole per liter (fMol/L)) in groundwater samples and apparent groundwater age dates (years), from the sand and gravel aquifer, Eglin AFB, near Niceville, FL, 4–6 February and 14–16 December 2020. Refer to Table 1 for specific site location name of site number.

Sample Basin and Number (Figure 3)	Sample Date	Sample Time	SF_6 Concentration (fMol/L)	Piston-Type Flow Model (Recharge Year)	Piston-Type Flow Model (Recharge Age, Years before Sample Collected)
Toms Creek Basin					
1	4 February 2020	1130	0.95	1991.5	28.6
2	4 February 2020	0925	1.97	2012	8.10
Turkey Creek Basin					
3	4 February 2020	1400	1.98	2002	18.1
4	4 February 2020	1530	1.80	2001	19.1
5	4 February 2020	1815	1.54	1996.5	23.6
6	16 December 2020	850	0.89	2004.5	16.5
Rocky Creek Basin					
7	5 February 2020	0900	1.22	1995	25.1
8	5 February 2020	1110	2.21	2004	16.1
9	5 February 2020	1430	1.27	1995.5	24.6
10	14 December 2020	1634	3.28	2016	5.00
Swift Creek Basin					
11	5 February 2020	1630	2.03	2007.5	12.6
12	15 December 2020	1446	1.53	1998.5	22.5
Deer Moss Creek Basin					
13	6 February 2020	0840	2.19	2005.5	14.6
15	6 February 2020	1000	2.15	2008.5	11.6
19	14 December 2020	1146	1.43	1998	23.0
Mill Creek Basin					
21	14 December 2020	852	2.43	2007.5	13.5
22	15 December 2020	1526	1.49	1996	25.0

Table 5. Sample location name and number, concentrations of methane (CH_4), carbon dioxide (CO_2), nitrogen (N_2), oxygen (O_2), and argon (Ar), in milligrams per liter (mg/L), in groundwater samples, Eglin AFB, near Niceville, Florida, February and December 2020. Refer to Table 1 for specific site location name of site number. All concentrations rounded to 2nd decimal place.

Sample Basin and Number (Figure 3)	Sample Date	Sample Time	Recharge Altitude (m above Mean Sea Level)	CH_4 (mg/L)	CO_2 (mg/L)	N_2 (mg/L)	O_2 (mg/L)	Ar (mg/L)
Toms Creek Basin								
1	4 February 2020	1130	33	0.00	12.34	16.48	8.04	0.59
2	4 February 2020	925	45	5.70	24.56	13.25	0.24	0.52
Turkey Creek Basin								
3	4 February 2020	1400	45	0.00	9.93	17.71	8.90	0.61
4	4 February 2020	1530	60	0.00	18.32	17.36	8.86	0.60
5	4 February 2020	1815	57	0.00	24.26	17.91	6.31	0.63
6	16 December 2020	850	54	12.73	199.13	9.62	0.09	0.37

Table 5. *Cont.*

Sample Basin and Number (Figure 3)	Sample Date	Sample Time	Recharge Altitude (m above Mean Sea Level)	CH_4 (mg/L)	CO_2 (mg/L)	N_2 (mg/L)	O_2 (mg/L)	Ar (mg/L)
Rocky Creek Basin								
7	5 February 2020	900	60	0.00	26.07	16.78	8.59	0.61
8	5 February 2020	1110	76	0.00	29.79	17.85	2.28	0.62
9	5 February 2020	1430	60	0.00	19.86	16.95	7.88	0.61
10	14 December 2020	1634	33	5.41	83.04	16.39	0.09	0.52
Swift Creek Basin								
11	5 February 2020	1630	45	0.00	12.78	15.94	8.51	0.57
12	15 December 2020	1446	33	2.14	88.93	17.10	0.08	0.61
Deer Moss Creek Basin								
13	6 February 2020	840	45	0.00	14.89	17.08	6.38	0.59
16	6 February 2020	1000	45	0.00	17.59	16.08	5.30	0.57
19	14 December 2020	1146	33	1.74	34.03	16.01	0.08	0.56
Mill Creek Basin								
21	14 December 2020	852	36	0.19	43.69	17.42	0.08	0.63
22	15 December 2020	1526	33	2.77	58.80	17.14	0.08	0.54

Stable Hydrogen and Oxygen Isotope Concentrations

The stable isotopes for the groundwater samples collected in February (Table 6) are shown in Figure 7. All samples (except for Site 5) plot above the local meteoric water line for precipitation [20], and both lines are offset from the global meteoric water line [21]. This offset of the local meteoric water lines from the global meteoric water line reflects the slightly heavier (enriched in percent heavier isotope) δ^2H values characteristic of regional precipitation rapidly removed from the atmosphere following recharge. All three lines have similar slopes and most likely reflect the isotopic equilibration during cloud formation. The slight offset of the heavier fractionation is due to evaporation during subsequent precipitation events that led to recharge in the basins. The isotopically heaviest samples (i.e., less negative values for δ^2H and δ^{18}O) were collected at two of the three headwater sites (Sites 3 and 4) 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 [7].

4.4. Recharge Extents

The recharge extents calculated for each sampling site are shown in Table 7 and graphically shown in Figure 8A–K (only the boldface most probable distances were used for the plot. In addition, the unnumbered sites shown in some figures represent the sampling locations of previous workers in the study area). When combined with the representative values of hydraulic conductivity for the upper part of the sand and gravel aquifer, the ages reveal that the recharge occurred from about 222 to 2011 m from the creeks. For most sites, recharge was located farther from the creek in headwaters compared to sites located downstream. The recharge area was also greater for headwaters and was more narrow for downstream sites using qualitative flow-net analysis.

Table 6. Sample location name and number, sample data and time, and results of stable hydrogen (δ^2H) and oxygen (δ^{18}O) isotopes (in per mil, ‰), Eglin Air Force Base and surrounding area near Niceville, Florida, 4–6 February 2020. Refer to Table 1 for specific site location name of site number.

Sample Name and Number (Figure 3)	Sample Date	Sample Time	δ^2H (‰)	δ^{18}O (‰)
Toms Creek Basin				
1	4 February 2020	1130	−19.28	−3.87
2	4 February 2020	925	−20.24	−4.04
Turkey Creek Basin				
3	4 February 2020	1400	−16.12	−3.48
4	4 February 2020	1530	−17.73	−3.63
5	4 February 2020	1815	−20.21	−3.83
Rocky Creek Basin				
7	5 February 2020	900	−20.16	−3.93
8	5 February 2020	1110	−20.34	−3.96
9	5 February 2020	1430	−19.28	−3.83
Swift Creek Basin				
11	5 February 2020	1630	−20.95	−3.99
Deer Moss Creek Basin				
13	6 February 2020	840	−19.74	−3.90
15	6 February 2020	1000	−21.54	−4.10

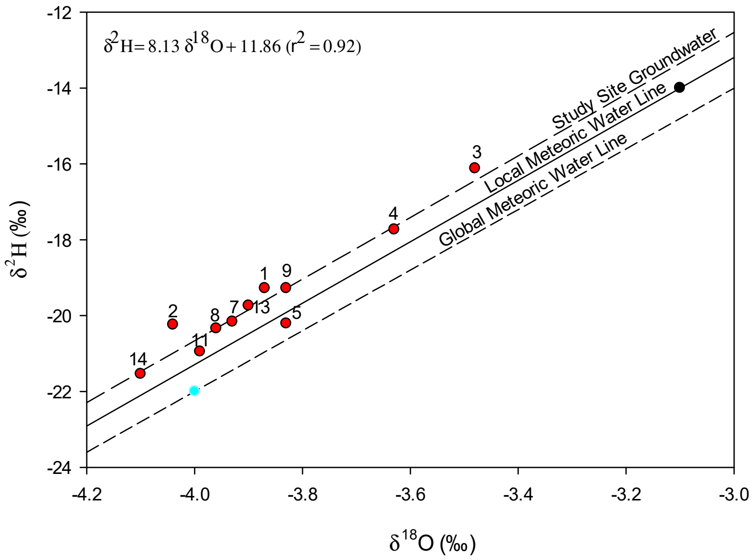
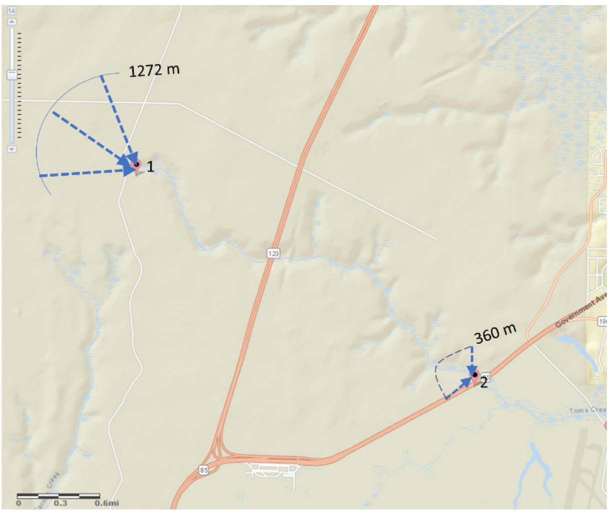


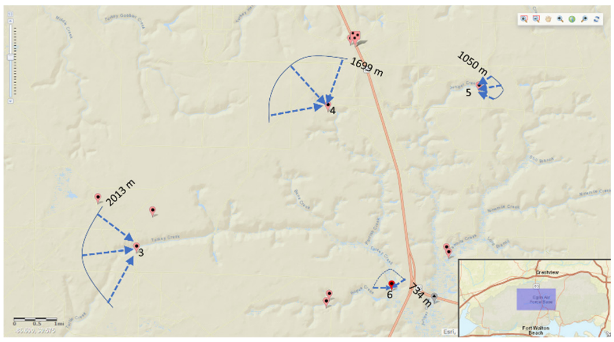
Figure 7. Stable δ^2H and δ^{18}O values, in per mil (‰), in groundwater collected 4–6 February 2020, beneath darter creeks, Eglin Air Force Base, near Niceville, Florida. The values for the study sites (numbered; Table 6) are plotted in relation to the global meteoric water line (Adapted from, [21]) and local meteoric water line (Adapted from, [20]). The equation for the line of the study site values is shown in the upper left-hand corner, with r^2 indicating the coefficient of determination.

Table 7. Sample location name and number, calculated recharge extent (m), as distance from the sampling site to upland areas, in meters, Eglin Air Force Base, near Niceville, Florida. Distances in **boldface** are the most probable lengths. Refer to Table 1 for specific site location name of site number.

Site Name and Number (Figure 3)	Time (Sulfur Hexafluoride (SF_6)-Based Age Date)	Distance (m), Hydraulic Conductivity, K, of 15 m/d	Distance (m), Hydraulic Conductivity, K, of 30 m/d	Distance (m), Hydraulic Conductivity, K, of 38 m/d
Toms Creek Basin				
1	28.6	**1272**	2545	3181
2	8.1	**360**	720	900
Turkey Creek Basin				
3	18.1	**805**	**1610**	**2013**
4	19.1	**849**	**1699**	2124
5	23.6	**1050**	2100	2625
6	16.5	**734**	1468	1835
Rocky Creek Basin				
7	25.1	**1116**	2233	2792
8	16.1	**716**	1432	1791
9	24.6	**1094**	2189	2736
10	5	**222**	**445**	**556**
Swift Creek Basin				
11	12.6	**560**	**1121**	**1401**
12	22.5	**1001**	2002	2503
Deer Moss Basin				
13	14.6	**649**	1299	1624
15	11.6	**516**	1032	1290
19	23	**1023**	2047	2558
Mill Creek Basin				
21	13.5	**600**	1201	1501
22	25	**1112**	2225	2781

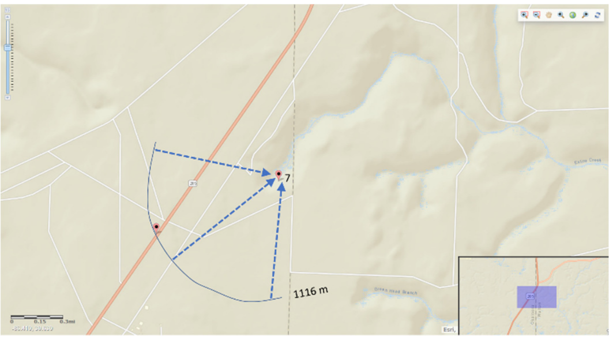


(**A**)



(**B**)

Figure 8. *Cont.*



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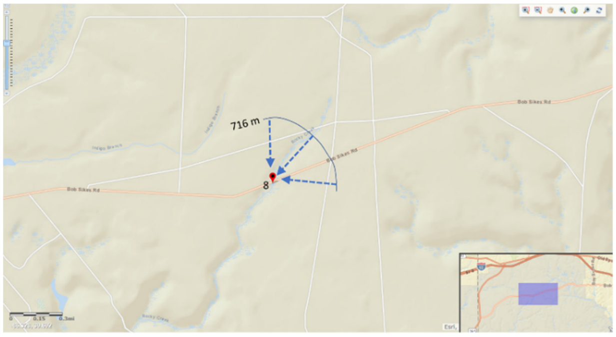

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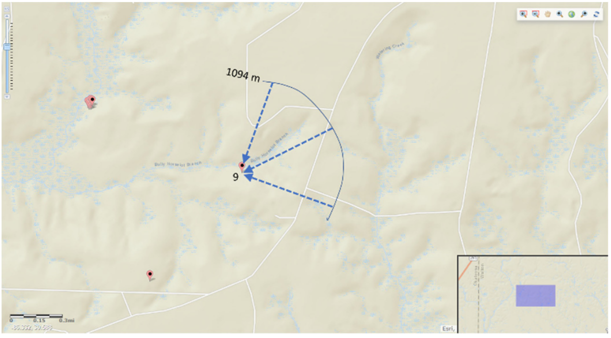

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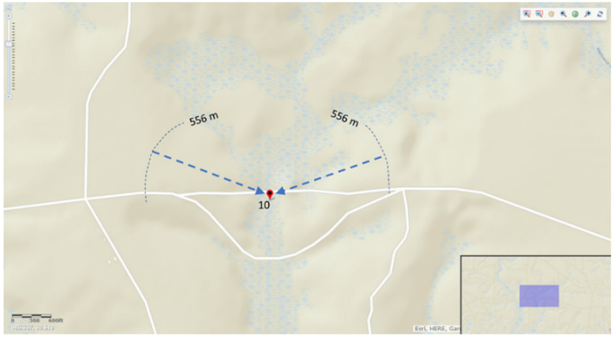
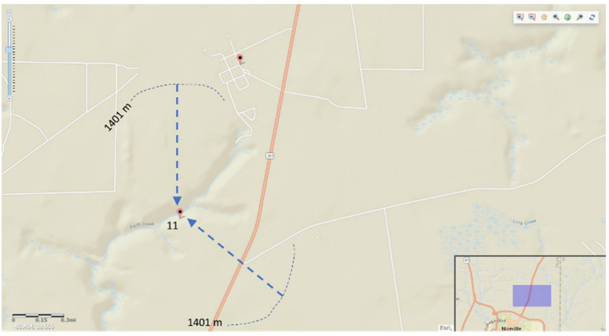
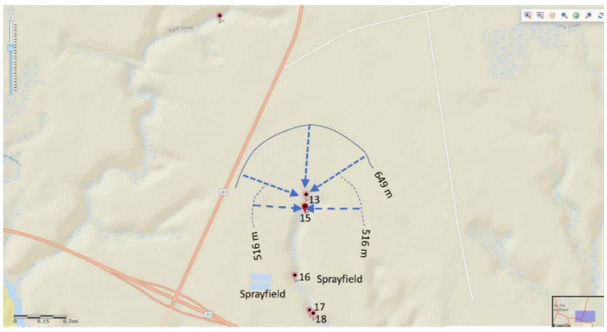


(**F**)

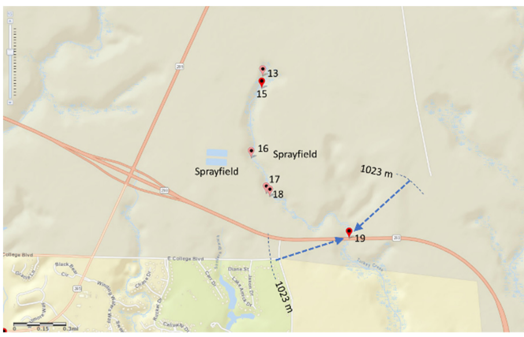


(**G**)

(**H**)

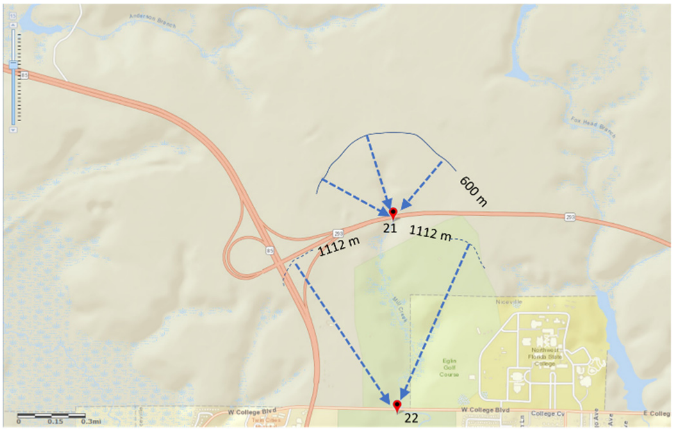


(**I**)



(**J**)

Figure 8. *Cont.*



(**K**)

Figure 8. (**A**) The recharge extent for headwater Site 1 and downstream Site 2, Toms Creek basin (Table 7). (**B**) The recharge extents for headwater Sites 3 to 5 and downgradient Site 6, Turkey Creek basin (Table 7). Unnumbered sites are from previous work done by others in the study area. (**C**) The recharge extent for headwater Site 7, Rocky Creek basin (Table 7). (**D**) The recharge extent for headwater Site 8, Rocky Creek basin (Table 7). (**E**) The recharge extent for headwater Site 9, Rocky Creek basin (Table 7). Unnumbered sites are from previous work done by others in the study area. (**F**) The recharge extent for downstream Site 10, Rocky Creek basin (Table 7). (**G**) The recharge extent for headwater Site 11, Swift Creek basin (Table 7). Unnumbered site is from previous work done by others in the study area. (**H**) The recharge extent for downstream Site 12, (Table 7). Unnumbered site is from previous work done by others in the study area. (**I**) The recharge extents for headwater Sites 13 and 15, Deer Moss Creek basin (Table 7). Sprayfields are located in the uplands on both sides of Deer Moss Creek. (**J**) The recharge extent calculated for downstream Site 19, Deer Moss Creek basin (Table 7). Sprayfields are located in the uplands on both sides of Deer Moss Creek. (**K**) The recharge extents calculated for headwater Site 21 and downstream Site 22, Mill Creek basin (Table 7). Only the boldface most probable distances were used. Dashed where approximated.

The recharge extent for the headwater (Site 1) of Toms Creek basin was calculated to be about 1272 m from the sampling site (Table 7, Figure 8A). The area of recharge estimated covers a broad upland area. In contrast, the recharge extent calculated for downstream Site 2 was only about 360 m from the sampling site and limited to a narrow extent on either side of the creek.

The recharge extent for the headwaters of Turkey Creek basin was calculated to be about 2013 m for Turkey Creek (Site 3), about 1699 m for Parrish Creek (Site 4), and about 1050 m for Juniper Creek (Site 5) (Table 7, Figure 8B). The area of recharge estimated for each headwater site covers a broad upland area. In contrast, the recharge extent calculated for the downstream location (Site 6) was only about 734 m from the sampling site and limited to a narrow extent on either side of the creek (Figure 8B).

The recharge extent was calculated to be about 1116 m for headwater Site 7 of the Rocky Creek basin, about 716 m for headwater Site 8, and about 1094 m for Site 9 (Table 7, Figure 8C–E, respectively). The area of recharge estimated for each headwater covers a broad upland area. In contrast, the recharge extent calculated for downstream Site 10 was only about 556 m from the sampling site (Figure 8F).

The recharge extent for Site 11 near the headwaters of Swift Creek basin was calculated to be about 1401 m (Table 7, Figure 8G). Moreover, the recharge extent calculated for downstream Site 12 was almost as long, at about 1001 m (Figure 8H). This recharge extent for this downstream site is longer than the extents for the 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.

The recharge extent for headwater Sites 13 and 15 of Deer Moss Creek were calculated to be about 649 m and about 516 m, respectively (Table 7, Figure 8I). The recharge extent for the main headwater site (Site 13) covers a large area, whereas the slightly downstream headwater site (Site 15) has recharge extents of narrow areas on either side of the creek. The recharge extent calculated for downstream Site 19 was longer than for both headwater sites, at about 1023 m, and limited to a narrow extent on either side of the creek Figure 8J). This long recharge extent for a downstream site may be because this site is located in a more urbanized area.

The recharge extent for Site 21 near the headwaters of Mill Creek basin was calculated to be about 600 m (Table 7, Figure 8K). The recharge extent calculated for downstream Site 22 was almost twice as long, at about 1112 m, and was limited to a narrow extent on either side of the creek. This recharge extent for this downstream site is longer than the extents for the previous downstream sites, perhaps because those were in more natural areas and this site is located in a more urbanized area.

5. Discussion

This study determined that the residence time of the groundwater that supports the flow in the six creeks that provide habitat for the Okaloosa darter is between about 5 and 28 years. This timeframe between the recharge in upland areas and discharge to creeks means resource managers could consider shifting to longer duration monitoring to be temporally commensurate with the anticipated outcomes for management activities. For example, darter populations near the 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, with less time available for natural attenuations processes to decrease contamination, but the headwaters are also currently (2022) facing water quality challenges (William Tate, U.S. Fish & Wildlife Service, written commun., 2021).

In contrast to the more natural flow systems of the 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, creating a bias 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 in considering delisting of the Okaloosa darter from the Endangered Species List.

Groundwater discharge to creeks is an important, but often unrecognized, factor in the health of fish communities and ecosystems, both in terms of water quantity and water quality. Groundwater provides the majority of streamflow between precipitation events and provides a relatively constant water temperature not affected by changes in solar radiation caused by shading, or diurnal or seasonal changes in air temperature. Cooler groundwater temperatures also facilitate higher levels of dissolved oxygen, which enhances fish spawning and rearing [25]. Our study further strengthens this coupling between groundwater discharge and fish communities and provides additional impetus for fisheries biologists to consider the inclusion of groundwater investigations as part of their routine surface water assessments.

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