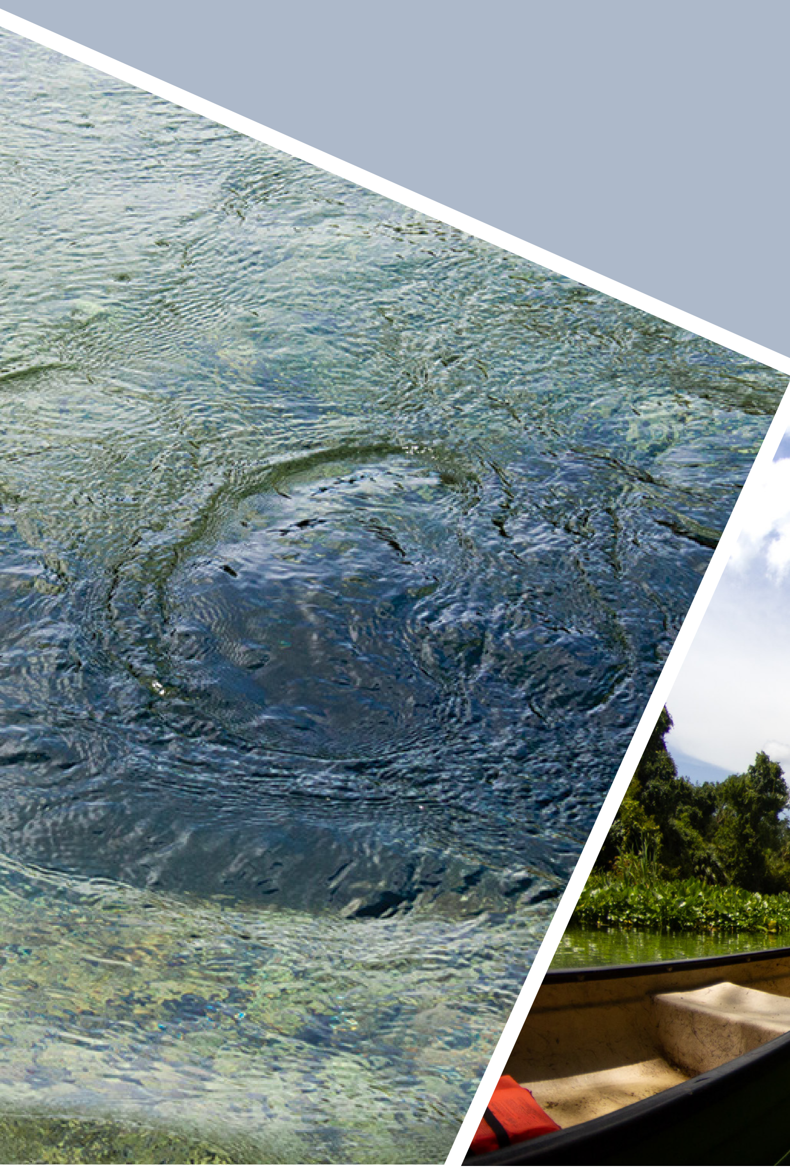
WEKIWA BMAP SITE ASSESMENT, GAP ANALYSIS, and REVIEW

8 September 2021

Prepared for:

Orange County Environmental
Protection Division
3165 McCrory Pl #200
Orlando, FL 32803

Orange County EPD PO #C18901108



DRUMMOND CARPENTER engineering + research

ORANGE COUNTY GOVERNMENT FLORIDA

ECT Environmental Consulting & Technology, Inc.

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Final Report

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Prepared by:

Drummond Carpenter, PLLC
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8 September 2021

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In accordance with Chapter 471 of Florida Statues, this Report has been prepared under the direct supervision of a registered Professional Engineer in the State of Florida.

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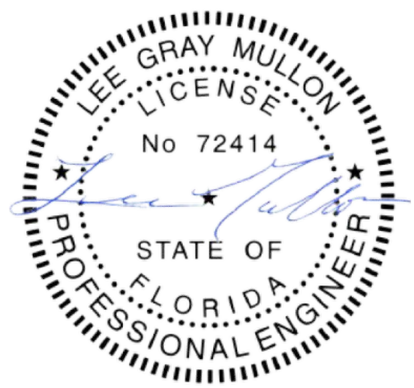

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September 8, 2021
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ACRONYMS

BMAP	Basin Management Action Plan
DO	Dissolved Oxygen
ECT	Environmental Consulting and Technology, Inc
ECFTX	East-Central Florida Transient Expanded
EVS	Earth Volumetric Studio
FDEP	Florida Department of Environmental Protection
FGS	Florida Geological Survey
FDOH	Florida Department of Health
ft^3/s	cubic feet per second
IAS	Intermediate Aquifer System
In	inches
OCEPD	Orange County Environmental Protection Division
OSTDS	Onsite Treatment and Disposal Systems
O	Oxygen
N	Nitrogen
NO_3-	Nitrate
NO_x-T	Total Nitrate + Nitrite
NSILT	Nitrogen Source Inventory Loading Tool
R^2	R-squared
SAS	Surficial Aquifer System
SIAR	Stable Isotope Analysis in R
SJRWMD	St. Johns River Water Management District
STORET	STOrage and RETrieval
PCA	Principal Component Analysis
PFA	Priority Focus Area
TOC	Total Organic Carbon
TMDLs	Total Maximum Daily Loads
UCF	University of Central Florida

UFA	Upper Floridan Aquifer
WIN	Watershed Information Network
δ	delta or "del"
µg/L	Micrograms per liter
µm	Micrometers
mg/L	Milligrams per liter

1. INTRODUCTION

This document serves as the Final Report deliverable for Task 9 as outlined in the Drummond Carpenter, PLLC (Drummond Carpenter) Scope of Work for the Wekiwa BMAP Gap Analysis project, under Orange County contract Y18-901, PO C18901108. This work has been performed for Environmental Consulting and Technology, Inc (ECT) per Work Order No. S-200232-0001-18RA.

1.1. Background

Groundwater quality sample collection using nitrate isotope forensic analysis has been ongoing within the Wekiwa Basin Management Action Plan (BMAP) area since at least 1999, with conventional groundwater nitrogen analysis beginning decades earlier. This effort was undertaken because of the long-term decline in water quality of the Wekiwa Spring and Wekiva River system, which has been identified as impaired due to excessive nitrate. A total maximum daily load (TMDL) of nitrate for Wekiwa Spring (2008) and a BMAP (2018) have been established by the Florida Department of Environmental Protection (FDEP) to address the biological imbalance caused in part by the high nitrate concentrations in groundwater discharging to Wekiwa Spring.

In 2009, the St. Johns River Water Management District (SJRWMD) and FDEP completed a nitrate sourcing study of the Wekiva River basin which concluded that fertilizer application within the Wekiwa springshed was the predominant source of nitrate loading. Starting in 2017, Orange County has collected additional groundwater data, including isotopic signatures $\delta^{15}N$ and $\delta^{18}O$, from select wells that have had historically elevated nitrate levels to better identify potential sources of nitrate loading within the Wekiwa springshed.

1.2. Project Goals

The primary goal of this project is to evaluate whether groundwater nitrate within the Wekiwa springshed can be attributed to nitrate sources, particularly the seasonal application of fertilizer, and how this information can inform future Wekiwa nitrate reduction strategies. To accomplish this goal, a review and gap analysis of Orange County's existing nitrate source tracking efforts were performed. Groundwater visualizations are included to help inform stakeholders on how dissolved nitrate can be transported through the aquifer located beneath the Wekiwa springshed.

1.3. Report Outline

The report outline for the remaining sections is presented below:

Section 2:	A detailed data and literature review of previous Wekiwa groundwater quality studies, nitrate isotope forensic analyses, and ongoing Orange County nitrate sourcing efforts
Section 3:	Gap analysis of existing County and other data in proportioning nitrate source allocations and understanding nitrate seasonality trends
Section 4:	Gap analysis of the existing isotope mixing model and improvement recommendations

Section 5: Gap analysis of groundwater fate and transport understanding

Section 6: Gap analysis summary

Section 7: Detailed recommendations based on the gap analysis

Section 8: Conclusions

2. DATA & LITERATURE REVIEW

Nitrate loading in a springshed is influenced by a multitude of factors including rainfall, season, land use, soil types, rates and forms of nitrogen inputs (CRISPS 2017). This section summarizes relevant data collected, reviewed, and organized as part of the project gap analysis described in the following sections.

2.1. Study Area

The Wekiwa BMAP area includes approximately half of the Wekiwa groundwater basin delineated by SJRWMD and includes the springs that contribute to the Wekiva River, Rock Springs Run, Little Wekiva River, and Blackwater Creek. The Wekiwa Priority Focus Area (PFA) is the administrative area of the basin where the Floridan Aquifer that is connected via groundwater pathways to Wekiwa Spring is most vulnerable to pollutants (FDEP 2017). The PFA boundary was defined by FDEP based primarily on available GIS data including springshed area, recharge rate, nitrogen loading, groundwater travel time (from the Upper Floridan Aquifer [UFA]), nitrogen leaching potential, and land use. The Wekiwa BMAP and PFA areas are shown in Exhibit 1. The area within the PFA is the primary focus of this study.

2.2. Isotope Introduction

Stable isotopes have atoms with the same number of protons but different number of neutrons and do not decay over time. Ratios of stable isotopes in compounds can provide clues on how the compound was formed and if it has been degraded (Kendall 1998; Roadcap et al. 2002).

Nitrate (NO_3^-) is made up of stable isotopes of nitrogen (N) and oxygen (O). The following are stable isotope forms of each element:

- stable forms of N, ^{15}N and ^{14}N, and
- stable forms of O, ^{18}O, ^{17}O, and ^{16}O.

The ratio of nitrogen isotopes is generally reported in permil (‰) relative to N standard in atmosphere, using delta (δ):

$$\delta^{15}N = [\frac{(^{15}N/^{14}N)_X}{(^{15}N/^{14}N)_{AIR}} - 1] \times 1000‰$$

where X indicates sample and AIR is reference standard gas (Kendall 1998). Similarly, the ratio of oxygen isotopes is generally reported in permil (‰) relative to O standard in Vienna Standard Mean Ocean Water (VSMOW), using delta (δ):

$$\delta^{18}O = [\frac{(^{18}O/^{16}O)_X}{(^{18}O/^{16}O)_{VSMOW}} - 1] \times 1000‰$$

where X is sample and VSMOW indicates reference standard water (Roadcap et al. 2002).

$\delta^{15}N$ and $\delta^{18}O$ of nitrate can be used as water quality tracers that provide information on nitrate sources and cycling. Stable isotope analysis of nitrate can be used as a forensic tool in pollutant source tracking efforts, as further described in the following sections.

2.2.1. Isotopic Mixing Models

Isotopic mixing models are used to attribute the source or sources of a particular compound. Relative to this effort, these mixing models can assume that nitrate samples collected from a waterbody of interest are mixtures of source nitrate compositions, such as fertilizer, wastewater and other sources. The source compositions and mixture composition are used to estimate the proportions of each source that contribute to the mixture. Although originally developed for ecological food web studies (Parnell et al. 2010), the Stable Isotope Analysis in R (SIAR) model has proven to be a useful tool in a broad range of research areas, including several other similar nitrate sourcing studies (Xue et al. 2012; Ransom et al. 2015; Matiatos 2016; Yang and Toor 2016; Xia et al. 2017; Meghdadi and Javar 2018).

SIAR is a Bayesian mass-balance mixing model which allows for overlap between source signatures and the ability to incorporate source signature variability (Ransom et al. 2015). These abilities are useful for "fingerprinting" nitrate contamination sources because individual sources have broad ranges of signature ratios, making traditional source attribution methods problematic and difficult to quantify probabilistically.

Three input datasets are used to build a SIAR model:

(1) isotopic signatures of the waterbody of interest,

(2) isotopic signatures of the nitrate sources, and

(3) fractionation factors (or trophic enrichment factors).

For this study, the waterbody of interest is groundwater within the Wekiwa springshed, and the isotopic data collected for each well are the first input for the SIAR model. The second input for the SIAR model is the set of isotopic signatures of the nitrate sources included in this study, referred to as source distributions. When discussing the mixing model, nitrate sources will be commonly referred to as "end members."

The final input is the set of fractionation factors which are used to account for the alteration of isotopic signatures caused by biogeochemical processing (Xia et al. 2017). The application of fractionation factors to nitrate sourcing studies is imperfect as SIAR was initially built for ecological food web studies. Consequently, SIAR was built for this third input to be in the form of trophic enrichment factors. While fractionation factors have been substituted directly for trophic enrichment factors in nitrate sourcing studies (Xia et al. 2017), the two are not simply interchangeable. Isotopic enrichment from one trophic level to a higher trophic level is essentially stepwise (Gilbert et al. 2019), and thus trophic enrichment factors in SIAR were designed to model this stepwise isotopic enrichment. Conversely, isotopic enrichment caused by denitrification is a continual, ongoing process, limiting the ability of trophic enrichment factors to accurately simulate denitrification in the SIAR model. A proposed work around to this factor dilemma is discussed in Section 4.2 of this report.

2.2.2. Source Distributions

A literature review of relevant studies was conducted to provide insight on contemporary applications of isotope tracer data and on the range of isotopic signatures of common nitrate sources, referred to as source distributions. Common nitrogen sources include atmospheric, soil, and manure and sewage, and fertilizers. Atmospheric nitrate accumulates from powerplant, vehicle, and agricultural emissions and is then removed from the atmosphere through wet or dry deposition. The soil source represents nitrate leached naturally from soil. Manure and sewage include nitrate originating from livestock waste, wastewater effluent, and septic systems. The fertilizer sources include nitrate originating from lawn or crop-applied nitrogen fertilizers.

The nitrate sources included in the mixing model of the current nitrate study are shown in Figure 1. Additional detail on the isotopic mixing model and end member source distributions are provided in Section 4.

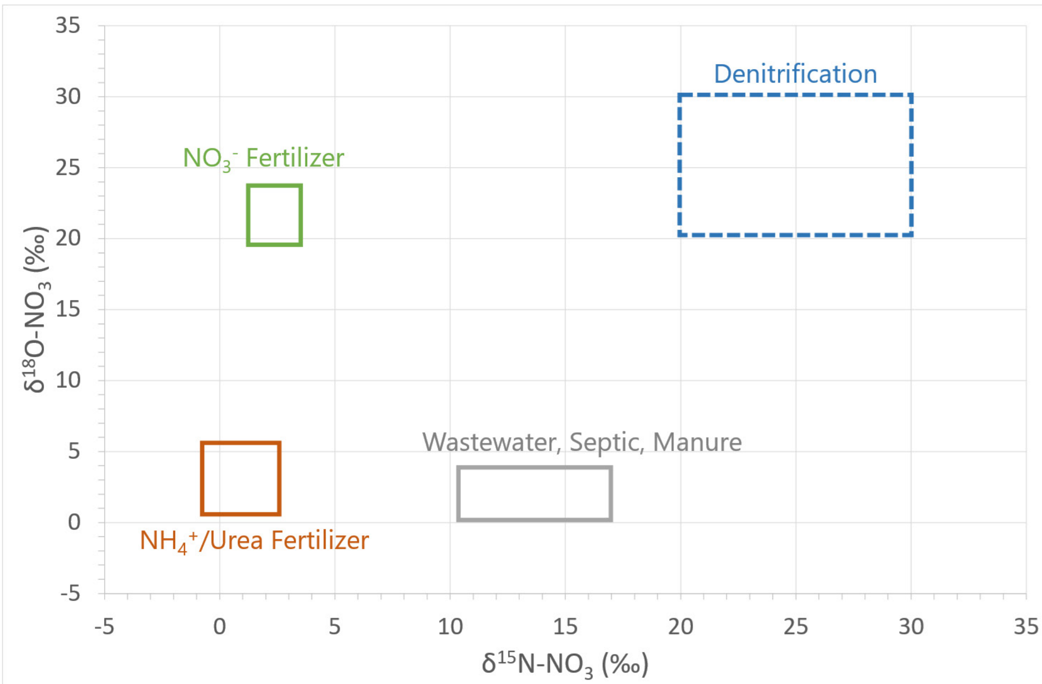


Figure 1. Source Distributions of End Members included in the Isotopic Mixing Model.

There are two defined fertilizer sources in the mixing model: (1) NO_3^- fertilizer and (2) NH_4^+/Urea fertilizer. Each of these fertilizers have distinct nitrate source distributions based on their respective isotopic signatures, which is a reflection of both the fertilizer production process and form of nitrogen in the fertilizer at the time of application.

The NO_3^- fertilizer source distribution box in the upper left of Figure 1, represents fertilizer that was applied as nitrate and was synthetically produced through the Haber-Bosch process, which uses atmospheric nitrogen and hydrogen gases under high pressure and temperature to produce ammonia gas that is then condensed to form anhydrous ammonia, i.e., liquid ammonia. This process produces nitrate with an isotopic signature that is similar to atmospheric nitrogen and oxygen, which creates relatively enriched $\delta^{18}O$ and low $\delta^{15}N$ signatures (Kendall et al. 2007). The NH_4^+/Urea fertilizer source distribution box in lower left of Figure 1, represents fertilizer that was applied as either urea or ammonium and converted to nitrate through microbially-driven processes in the soil after application. This microbial process produces nitrate with an isotopic signature with relatively low $\delta^{18}O$ and low $\delta^{15}N$ signatures (Kendall et al. 2007).

While understanding the distinction between the two fertilizer signatures is key to sourcing nitrate to fertilizer, the focus of this study remains on the total contribution of fertilizers to nitrate loading for informing fertilizer management strategies. Both types of fertilizers are available for residential use within Orange County. Fertilizer bags available at local hardware stores in Orange County commonly contain a mixture of urea nitrogen, ammonium nitrate nitrogen, and nitrate nitrogen. Therefore, mixing model results will include discussion of total fertilizer loading estimates.

2.2.3. Prior Information

Bayesian mixing models include the ability to incorporate prior distribution information to guide the model in the likely range of values to determine source proportions. Such prior information can include results from previous studies, model runs, or expert opinion based on *a priori* knowledge. If priors are not incorporated, the model assumes that all potential sources are treated equally.

2.2.4. Denitrification

Denitrification is the process by which nitrate is reduced to nitrogen gas by denitrifying bacteria. Denitrification is a type of isotopic fractionation, which can be defined as the relative proportioning of heavy and light isotopes caused by chemical or physical processes. Isotopic fractionation is an important consideration in isotopic analysis, with denitrification often causing significant fractionation in nitrate.

During denitrification, ^{14}N-nitrate is consumed at a faster rate than ^{15}N-nitrate, causing an increase in the ratio of ^{15}N:^{14}N (i.e., enrichment of $\delta^{15}N$) in the remaining nitrate pool. Similarly, $\delta^{18}O$ is enriched during denitrification as ^{16}O-nitrate is consumed faster than ^{18}O-nitrate. Since denitrification alters the isotopic signature of nitrate from its source signature, consideration of the role of denitrification is necessary to accurately interpret nitrate sources using isotopic signatures. For example, if denitrification is not considered, elevated $\delta^{15}N$ values may be interpreted as septic or manure sources based on source distributions in Figure 1; however, nitrate with elevated $\delta^{15}N$ values could originate from a NH_4^+/Urea fertilizer source that was enriched through denitrification.

2.3. Wekiwa Spring Hydrogeology

Nitrate transport to Wekiwa Spring is dependent on various aquifer properties, the presence of conduits, and denitrification rates. Hydrogeologic data were obtained from the Florida Geological Survey (FGS), including locations of wells with available lithology logs, UFA potentiometric surfaces, and a statewide geology map. Each dataset was downloaded from the relevant FGS and FDEP database. Exhibit 2 displays the surface geology of the study area, as well as cross sections developed based on the lithology logs within the study area. The surface formation at assessed monitoring locations is the Cypresshead Formation. The Cypresshead Formation is predominately composed of quartz sand ranging from fine to coarse-grained with variable amounts of clay (Scott 1992).

Exhibit 3 shows the UFA potentiometric surface from September 2017, the most recently available potentiometric surface from FDEP, and UFA recharge rates within the Wekiwa PFA. The UFA recharge rates dataset was acquired from the SJRWMD database[1]. Most study wells fall in high recharge areas. High recharge areas represent greater than 15 inches (in) per year (yr) recharge, medium recharge 5 to 15 in/yr, and low recharge 1 to 5 in/yr (Boniol and Mouyard 2016). Discharge areas occur where the UFA potentiometric surface is higher than the elevation of the water table, and movement of groundwater is upward through spring flow and groundwater withdrawals.

Groundwater samples have been taken, by others, from three aquifer systems for the current nitrate sourcing study:

(1) the surficial aquifer system (SAS),

(2) intermediate aquifer system (IAS),

(3) and the Upper Floridan Aquifer (UFA).

The SAS is composed of predominately unconsolidated to poorly consolidated quartz sands with variable amounts of clayey sand, clay, and shell. The SAS extends from the land surface to the uppermost mappable clay layer which defines the top of the IAS. The IAS is composed primarily of low permeability clay and silt sediments with lenses of sand, shell, or limestone serving as local aquifers within the IAS. The IAS lies between the SAS and UFA and generally serves as a confining unit for the UFA. The UFA is composed predominately of limestone and dolomite. The UFA is characterized by karst dissolution features including cavities and conduits that create preferential flow paths and heterogeneous groundwater travel times. Travel times have an important influence on denitrification that is discussed in Section 2.4.6. The cross sections on Exhibit 2 depict the inferred thicknesses of the SAS, IAS, and UFA layers from the available well lithology logs.

Findings from the Central Florida Water Initiative (Basso 2020) show that groundwater generally infiltrates from the SAS to the IAS to the UFA and finally migrates to the spring. In the SAS and IAS layers, groundwater flow directions generally mirror surface topography, with limited horizontal travel and predominant vertical flow into the UFA. Once in the UFA, the groundwater travels relatively rapidly to Wekiwa Spring. Several studies report that Wekiwa Spring discharge originates primarily from the UFA (Toth 1999; Briggs et al. 2007; Harrington et al. 2010; FDEP 2015). Exhibit 4 shows the head difference from the SAS to UFA, and where potentiometric surface elevations exceed the SAS water table, upward groundwater movement may occur.

2.3.1. FDEP Wekiwa Groundwater Tracer Study

In 2014 and 2015, FDEP conducted two tracer tests to evaluate groundwater flow rates to Wekiwa and Rock Springs. For Wekiwa Spring, the tracer was injected in an UFA well located 1.5 miles southwest (upgradient) of Wekiwa Spring and arrived at the spring within 50 days, corresponding to a travel velocity of 137 feet/day. The UFA well is likely XDEPPBD based on location; however, a well name was not provided in the report. Using the results of the tracer test, groundwater transport within the UFA throughout the springshed could be more than 10 miles per year (FDEP 2017). Based on the reported

[1] http://data-floridaswater.opendata.arcgis.com/datasets/e740bfd1d37f46fea0e39529f18bd91c_0?selectedAttribute=RECH_RANGE

transport of 10 miles per year, the approximate boundary of a one-year travel area through the UFA around Wekiwa Spring is shown in Exhibit 1.

It is noted that groundwater travel time within the UFA does not equal the travel time of a dissolved nitrate source applied to the land surface. Fertilizer sources, septic sources, and other wastewater sources are generally applied at or near the ground surface and must infiltrate and recharge down through the surficial and intermediate aquifers before reaching the UFA. Generally, groundwater travel through the SAS and IAS is predominantly vertical to the UFA with limited horizontal travel. Still, groundwater travel time through the SAS and IAS can be longer than the more horizontal travel within the UFA, even though the travel distance within the UFA is typically far greater. This is due to the karst, porous nature of the UFA that may have significant conduit flow. Additionally, dissolved nitrate migration in aquifers have the potential to be affected due to adsorption, diffusion, and variable flow paths from matrix or conduit flow.

2.4. Literature Review

A thorough literature review of Wekiwa-related studies was completed. Key studies are summarized in this section with noteworthy general similarities in findings. Namely, fertilizers, onsite treatment and disposal systems (OSTDS) (septic systems), and wastewater are likely contributors to nitrate in the Wekiwa springshed, and fertilizers were consistently found to supply the largest contribution to nitrate loading. Each study addresses the uncertainty of nitrate source assessments and the need for additional data. The County’s current nitrate sourcing study has been collecting quarterly water quality and isotope data since 2017 to improve and build on these studies and reduce uncertainty in source allocations.

2.4.1. 2002 SJRWMD Study

A 2002 SJRWMD study by Toth and Fortich investigated nitrate concentrations, nitrate sources, and ages of water in the Wekiwa basin using the well network shown in Figure 2. The study used isotope data to conclude that lawn fertilizers and animal waste or sewage are the main sources of nitrate to Wekiwa Spring. Isotope data were also used to calculate that the mean age of Wekiwa Spring water is 17 years, while the mean age of groundwater in the basin is 27 years, suggesting a significant portion of spring water is coming from nearby “young” water sources. Areas south and southwest of the spring with high recharge rates were determined as the most influential sources of nitrate to Wekiwa Spring.

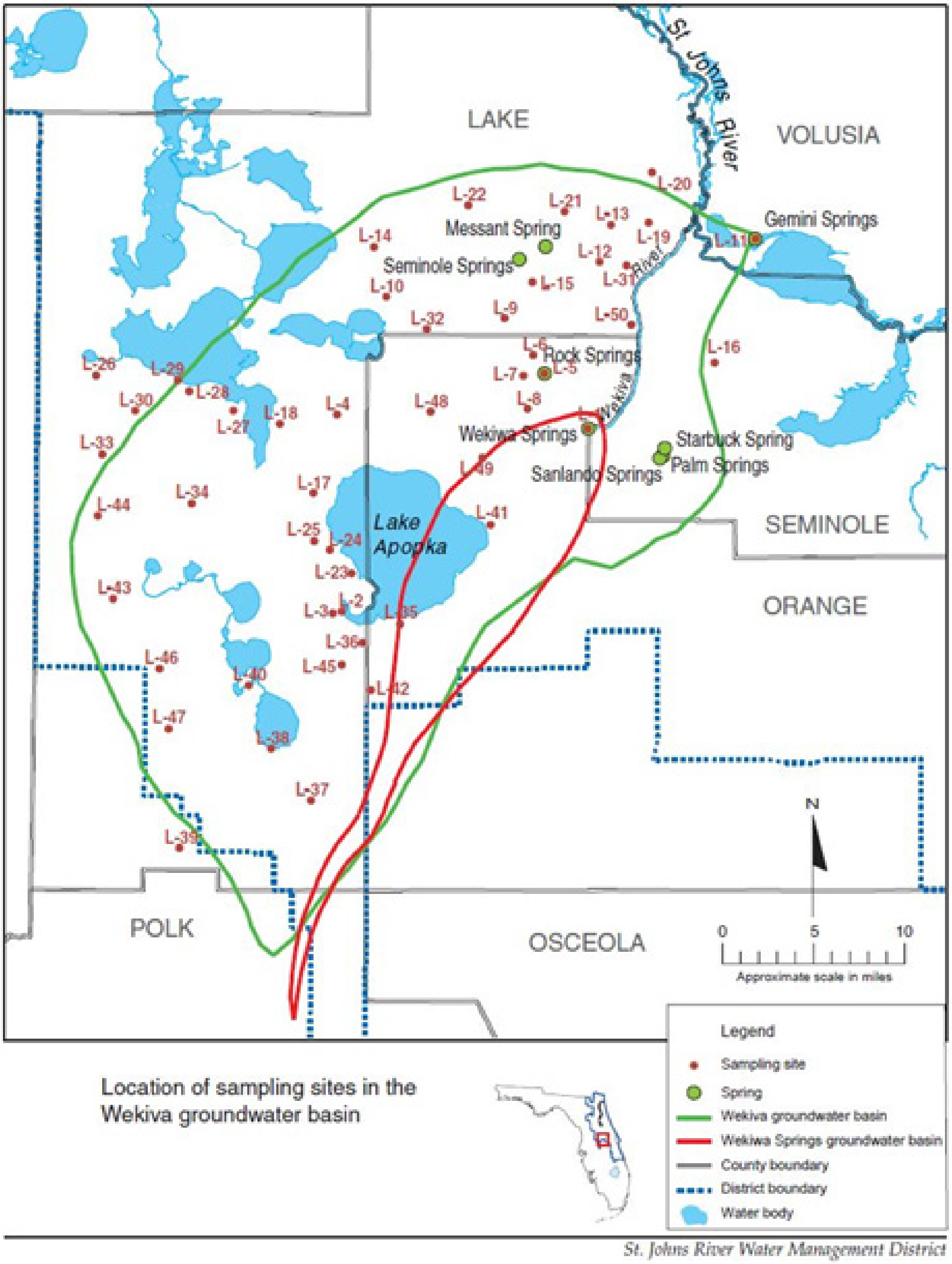


Figure 2. SJRWMD 2002 sampling sites (Modified from Fig. 6, Toth and Fortich 2002).

2.4.2. 2007 FDOH Study

A 2007 Florida Department of Health (FDOH) study assessed the role of OSTDS in contributing to nitrate loading within the Wekiwa study area. The FDOH study found that OSTDS were not as significant of a source of nitrate compared to fertilizer. OSTDS contributions to nitrate loading were estimated to be similar in magnitude to those from livestock, centralized wastewater, and non-agricultural, non-residential fertilizer use (Briggs et al. 2007). The fertilizer sources combined were attributed to 71% of all nitrate loading, though due to uncertainty associated with the assessment, the percent contributions by source were left out of the final report (Briggs et al. 2007).

2.4.3. 2009 and 2012 UCF Studies

Two University of Central Florida (UCF) studies from 2009 and 2012 examined residential fertilizer practices near Wekiwa Spring. The 2009 UCF study found that 84% of Wekiwa residents apply fertilizer to their lawn, and fertilizer is applied at an average frequency of 3.53 times/year (Souto et al. 2009). The 2012 UCF study explored methodology to connect fertilizer practices with socio-economic data to allow for better understanding of residential impacts on water quality (Souto and Listopad 2012). The findings of the study indicated correlations between fertilizer hot spots and the following:

- golf courses,
- newer homes,
- higher property values, and
- Caucasians within middle to middle-high income brackets (Souto and Listopad 2012).

2.4.4. 2010 MACTEC Study

A 2010 MACTEC study integrated nitrate sourcing findings from previous Wekiwa state-funded studies with water quality and isotopic data collected to better understand residential fertilizer inputs. The following primary nitrate sources were identified in the study: wastewater treatment facilities, OSTDS, fertilizer (agricultural, residential, golf course, and other), livestock, and atmospheric deposition. The contributors to nitrate loading in the Wekiwa study area were found to be the following:

(1) fertilizer accounting for 48% of total nitrate loading,

(2) OSTDS accounting for 26%,

(3) wastewater treatment facilities accounting for 12%, and

(4) Other sources including atmospheric or unattributed sources accounting for14% (MACTEC 2010).

2.4.5. 2010 FDEP Study

A 2010 FDEP study on Florida springs concluded the application of inorganic fertilizers has the potential to contribute the most significant nitrogen inputs per acre to groundwater and springs (Harrington et al. 2010). The same study concluded that in addition to fertilizers, domestic wastewater facilities and residential septic systems are likely significant contributors to nitrate in the Wekiwa-Rock Springs springshed.

2.4.6. 2012 Denitrification Studies

A regional study of 61 UFA springs determined denitrification is correlated with strong $\delta^{15}N$: $\delta^{18}O$ covariation, inversely correlated with dissolved oxygen, and alters $\delta^{15}N$ at the regional scale (Heffernan et al. 2012). The same study by Heffernan et al. (2012) concluded that approximately 75% of total nitrate input to the Wekiwa springshed is removed by denitrification in the UFA before discharging to Wekiwa Spring and nitrate enrichment of Wekiwa Spring is due primarily to inorganic fertilizers with contributions from organic sources.

Another regional study demonstrated that nitrate inputs to Florida springs are predominantly from non-point sources, and denitrification is detectable in aquifer waters with a relatively long residence time (Albertin et al. 2012). The same study by Albertin et al. (2012) calculated a 43% decline in nitrate concentrations and increases in $\delta^{15}N$ and $\delta^{18}O$ values for Wekiwa Spring from 2005 to 2008. This decline was attributed to below normal precipitation in 2008, which altered the hydrology of the aquifer contributing to spring discharge by reducing the proportion of conduit flow and increasing matrix flow. Matrix flows have longer residence times that allow for greater denitrification which the authors contend explains the observed decline in nitrate concentrations and isotopic enrichment in 2008.

A USGS study on denitrification potential of water in the UFA and Wekiwa and Rock Springs suggested denitrification could be responsible for the low ambient nitrate concentrations in the UFA (Byrne et al. 2012). The *in situ* rates of denitrification were calculated as $5x10^{-4}$ milligrams nitrogen per liter per day (mg N/L/day) based on groundwater age and the accumulation of nitrogen gas concentrations in laboratory samples (Figure 3).

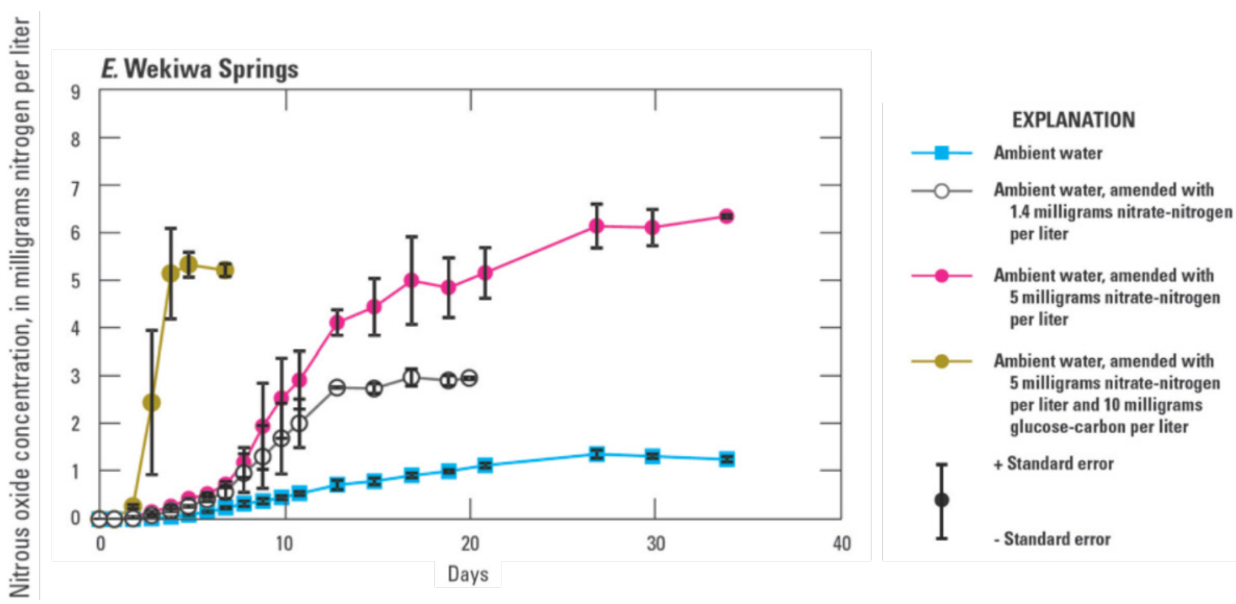


Figure 3. Nitrous oxide production by Wekiwa Spring-water samples during laboratory incubations to measure denitrification potential (Modified from Fig. 2, Byrne et al. 2012).

2.4.7. 2018 BMAP Report

The Wekiva River and Rock Spring Run were listed as impaired in 2007 based on elevated total phosphorus and nitrate-nitrogen concentrations and an imbalance in aquatic flora. In 2008, TMDLs for nitrate (286 µg/L) and total phosphorus (65 µg/L) were developed for Wekiwa Spring and Rock Springs. A Wekiwa BMAP, encompassing 513 square miles, was adopted to implement the TMDLs. The BMAP established the UFA as the source of water discharged by the springs. As part of the Wekiwa BMAP, FDEP developed the Wekiwa and Rock Springs Nitrogen Source Inventory Loading Tool (NSILT), which assigned percent contributions of nitrogen sources to total nitrogen loading for the springshed area. The top three contributors to the total nitrogen loading to groundwater were estimated as:

(1) fertilizers contributing 45% to total nitrogen loading,

(2) OSTDS contributing 29%,

(3) wastewater treatment facilities contributing 16%, and

(4) atmospheric, nurseries, and livestock operations contributing a combined 10% (FDEP 2018).

These source allocations are compared to results from a MACTEC (2010) study in Figure 4, which depict overall similar source allocations. The NSILT tool relies on many assumptions for important parameters that generate uncertainty in the model results including biochemical attenuation factors, density of septic systems, fertilizer application rates, and land use apportionments (Geosyntec 2018). To date, FDEP has not provided the uncertainties associated with the parameters used in the NSILT tool.

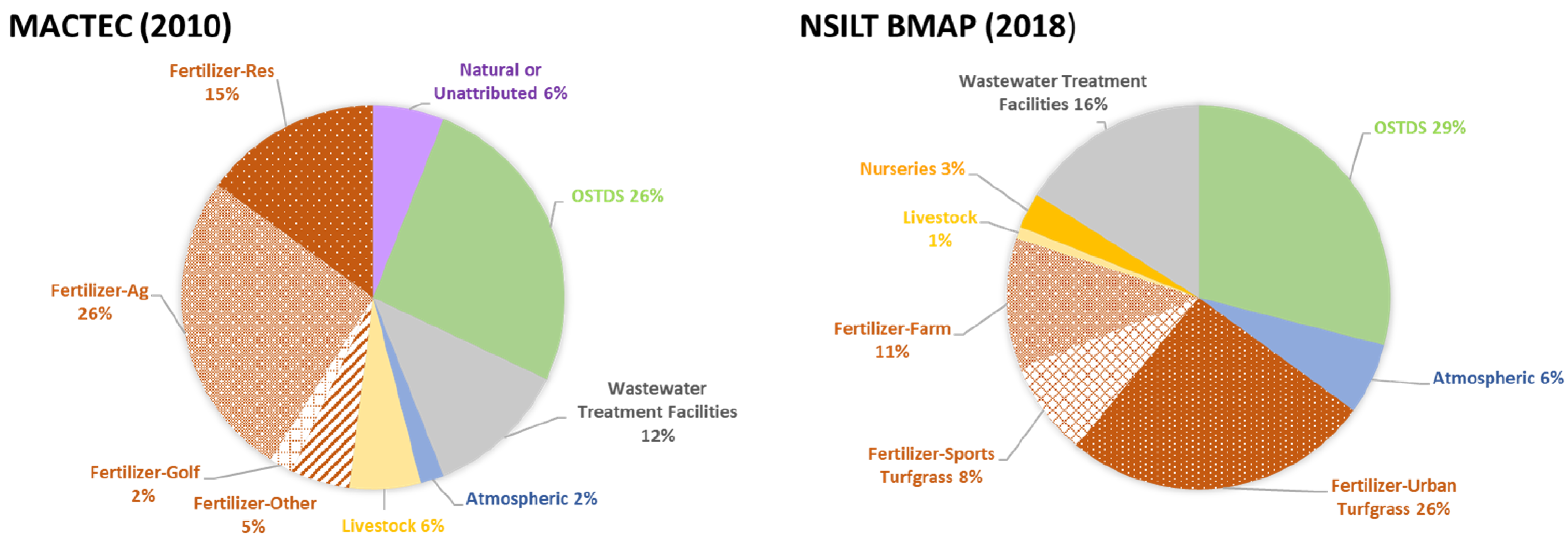


Figure 4. Comparison of MACTEC (2010) and NSILT BMAP (FDEP 2018) nitrate source allocations.

2.4.8. 2020 Nitrogen Sources in Florida Karst Springs

Canion et al. (2020) measured nitrate isotopes and wastewater indicators (sucralose and Cl:Br) in 50 wells at 38 sites and at 10 springs in Florida to better understand relative contributions of nitrogen sources to groundwater and inform nitrogen loading reduction strategies. A Bayesian mixing model, as described in Section 2.2 was used by Canion et al. (2020) to estimate contributions of nitrate sources in wells based on measured nitrate isotopes. Canion et al. (2020) included four sources of nitrate as end members in the mixing model: (1) wastewater (septic tank effluent and reuse water); (2) manure; (3) nitrate fertilizer, and (4) ammonium fertilizer. Nitrate originating from atmospheric deposition of nitrogen and naturally from organic matter in soil was determined to be insignificant relative to the magnitude of nitrate originating from other identified sources, and consequently, atmospheric and soil sources were not included in the mixing model to avoid unnecessary uncertainty. This study found that fertilizer or mixed fertilizer and wastewater were the primary sources of nitrogen loading to groundwater in residential areas.

2.4.9. 2021 Nitrogen Transport from Fertilizers Study

An Orange County 2021 study evaluated the transport dynamics of fertilizer nitrogen applied on residential lawns within the Wekiwa BMAP area under varying environmental conditions, application rates, and fertilizer types (Drummond Carpenter 2021). The study developed unsaturated zone and saturated zone flow and constituent fate and transport models to simulate the movement of nitrogen from fertilizer application on turfgrass on a residential lawn through the unsaturated zone to the groundwater until reaching Wekiwa Spring. Model results indicated that a portion of applied fertilizer nitrogen will likely leach, regardless of environmental conditions, application rate, or fertilizer type. This finding is consistent with a UF/IFAS publication on the fate of nitrogen applied to residential turfgrass in Florida that estimates <1 to 55% of applied nitrogen in fertilizer will leach to groundwater (Shaddox and Unruh 2018). Additional findings from this study are summarized in the following:

- As the fertilizer loading rate is increased, the nitrogen leaching to groundwater is increased.
- As the portion of slow-release nitrogen is increased in a fertilizer from 0 to 65% slow-release, the nitrogen uptake by turfgrass is increased and the leaching to groundwater is decreased.
- Fertilizer nitrogen applied before high precipitation events is susceptible to greater leaching compared to fertilizer nitrogen applied during periods without a high precipitation event.
- For the same fertilizer composition, leaching increases with higher annual recharge and a shallower water table compared to average conditions.
- Under modeled conditions, fertilizer loading rate has a greater impact on nitrate concentrations at Wekiwa Spring than the annual precipitation patterns, groundwater gradient, or depth to water table.

2.5. Wekiwa Data Collected by Other Consultants

Orange County Environmental Protection Division (OCEPD) provided Wekiwa-related water quality and isotope data collected by other consultants via email on March 10, 2020, May 13, 2020, and August 13, 2021. The data provided include water quality data for the spring vent and 22 monitoring stations. In the March 10, 2020 data transfer, results from an initial isotopic mixing model performed by Wood Environment and Infrastructure Solutions, Inc. (Wood 2020) were included in addition to the water quality data. This initial analysis by Wood (2020) concluded there are distinct areas of higher nitrogen within the springshed and multiple sources of nitrogen contributing to Wekiwa Spring.

Wood has since created a revised final isotopic mixing model with additional isotopic data, modifications to the included wells, and modifications to end members (Wood 2021). The findings from the final mixing mode indicate fertilizers are a top contributor to nitrate. The Gap Analysis was performed prior to the completion of this final mixing model and will contain recommendations that have already been implemented by Wood in their September 2021 report.

Exhibit 5 shows the location of wells within the Wekiwa PFA used in the current Wekiwa study conducted by the County, organized based on median nitrate concentrations collected by the County from November 2017 to March 2020. The aquifer unit in which each well is screened is indicated by color in Exhibit 3. Isotope data was collected for wells with higher nitrate concentrations, generally greater than 1 mg/L as nitrate-N. Currently, one well (MWBU) within the UFA has isotope data.

This Gap Analysis primarily relied on nitrate measurements provided by the County for the analysis herein in lieu of nitrite, which is generally an insignificant component of the dissolved inorganic nitrogen observed in the well samples. Unless otherwise noted, nitrate values are used throughout this assessment.

2.6. Historical Precipitation Data

Historical precipitation data were downloaded from NOAA for Clermont and Plymouth stations, the nearest monitoring stations to Wekiwa with precipitation normal data[2]. Figure 5 shows monthly precipitation normals[3] for these stations from 1981-2010 (Arguez et al. 2010). The wet season from June-September corresponds to the restricted nitrate fertilizer period from the County's fertilizer ordinance, which was adopted in 2017.

[2] https://www.ncdc.noaa.gov/cdo-web/datasets

[3] A precipitation normal is a 30-year precipitation average (Arguez et al. 2010).

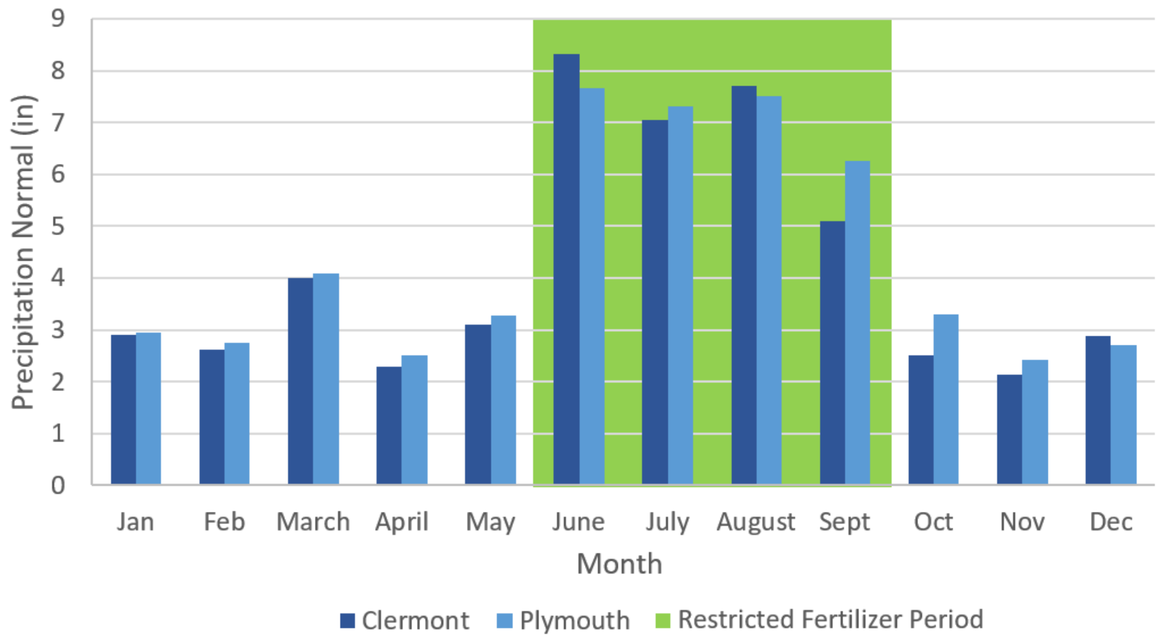


Figure 5. Monthly precipitation normals for Clermont and Plymouth stations from 1981-2010.

The current nitrate sourcing study uses samples collected starting in November 2017 through March 2020. The nearest rainfall monitoring station with a complete dataset for this time period is just north of Wekiwa Spring at Rock Springs (Station: 11303088). Data were downloaded from the SJRWMD online database[4] and are displayed in Figure 6. Elevated total precipitation values are observed during a few months outside of the wet season, including May 2018, December 2018, and October 2019, and isotopic samples were collected as part of the current nitrate study for December 2018 and October 2019. The remaining months when isotopic samples were collected are indicated in the figure.

[4] http://webapub.sjrwmd.com/agws10/hdsnew/map.html

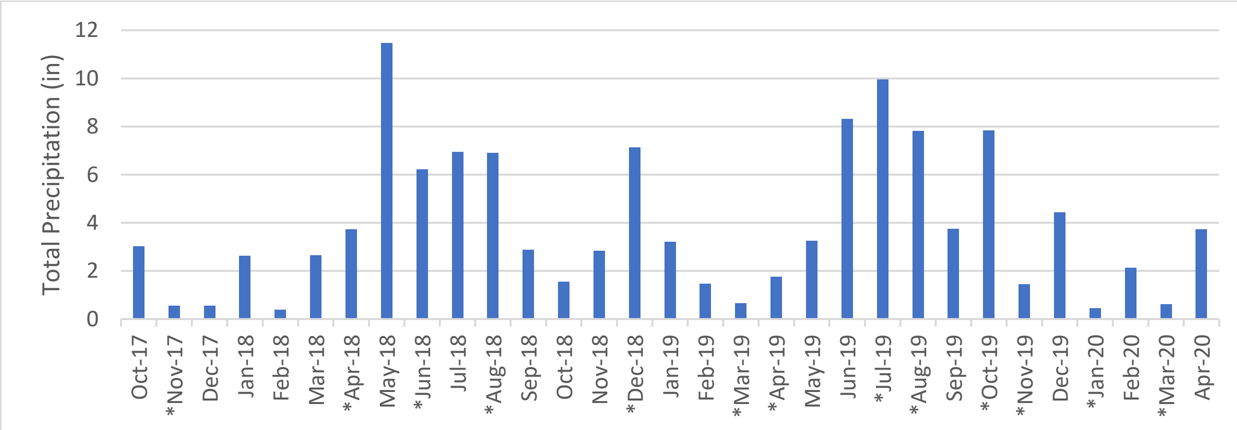


Figure 6. Monthly Precipitation Totals for Rock Springs Station during the current nitrate sourcing study sampling period included in this Gap Analysis: 2017-2020 (* indicates months when isotopic samples were collected).

2.7. Wekiwa Flow Measurements at the Spring Vent

Wekiwa Spring is a second-magnitude spring. Available discharge data for Wekiwa Spring at the Altamonte Springs (00371831) monitoring station were downloaded from the SJRWMD online database[5]. Point discharge data for this station are available at increasing frequency from 1932 to 2019. The average discharge for this flow monitoring location is 62 cubic feet per second (ft^3/s). Figure 7 shows (A) the discharge dataset from 1970 to 2019 and (B) a subset of the data available for the sampling period of the current nitrate sourcing study.

Figure 8 shows the relationship between discharge data and total nitrate + nitrite (NO_x-T) at Wekiwa Spring from 1990-2019. Discharge data and NO_x-T at Wekiwa Spring appear to be positively correlated. Fitting a linear regression model to the discharge and NO_x-T data resulted in a R-squared (R^2) value of approximatly 0.58. R^2, whichis a goodness-of-fit measure for linear regression models and indicates the percentage of variance in the dependent variable (NO_x-T) that the independent variable (discharge) can explain, meaning roughly 58% of NO_x-T values can be statistically explained by discharge. NO_x-T data were downloaded from the SJRWMD environmental database[6] for the Wekiwa Spring (73688) monitoring station.

Relationships between flow and nitrate at Wekiwa Spring have been described in a previous study by Albertin et al. (2012). This study attributed declines in nitrate concentrations to a low flow regime caused by below normal precipitation. This low flow regime is thought to reduce conduit flow resulting in longer groundwater travel times which allows for greater amounts of denitrification to occur before groundwater discharges at the spring.

[5] http://webapub.sjrwmd.com/agws10/hdsnew/map.html

[6] http://webapub.sjrwmd.com/agws10/edqt/

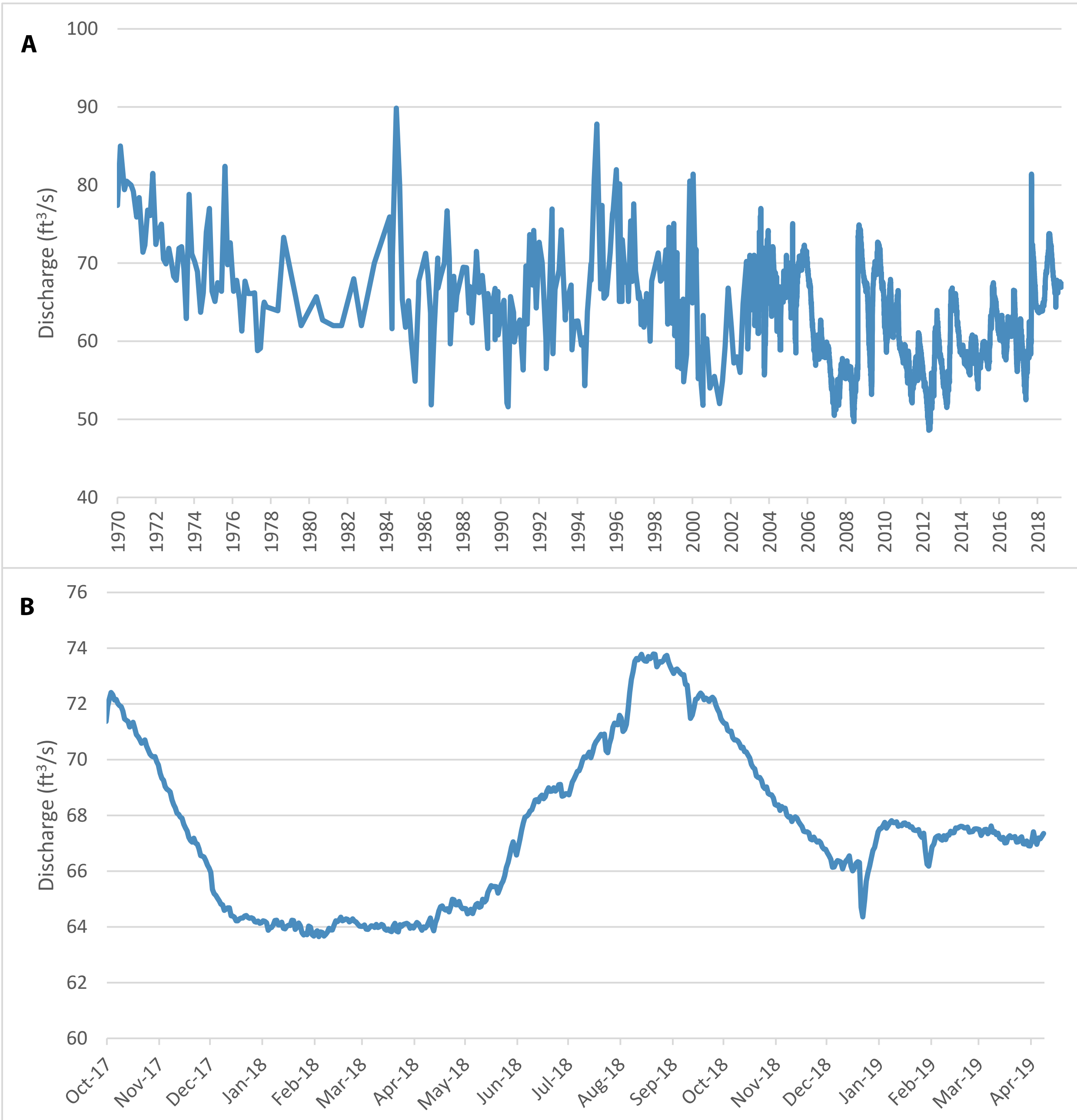
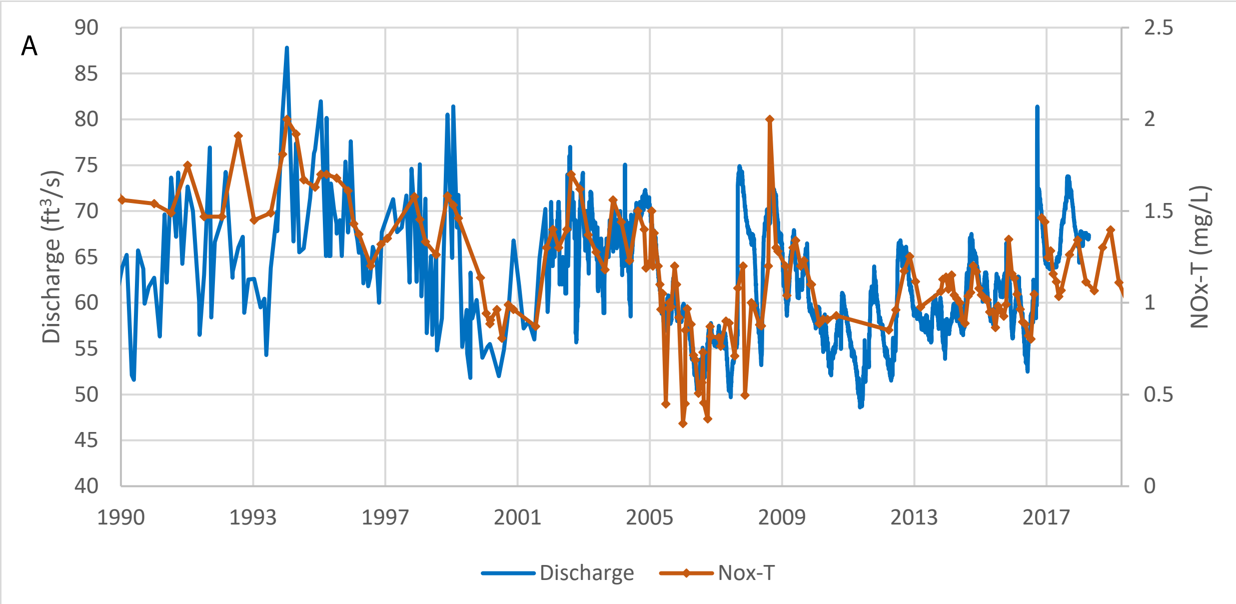


Figure 7. Discharge data for Wekiwa Spring at monitoring station, Altamonte Springs (00371831), from (A) 1970-2019 and (B) 2017-2019 (SJRWMD 2020).



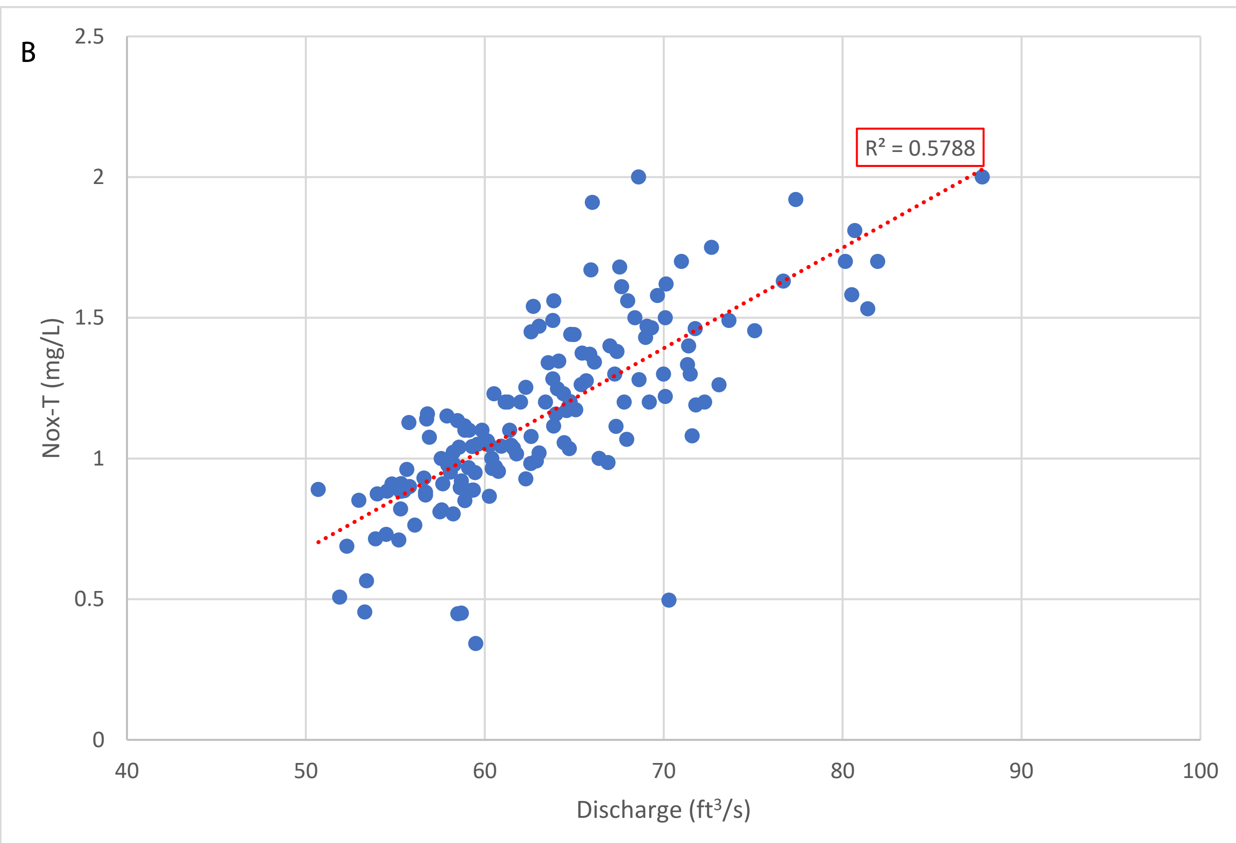


Figure 8. (A) Wekiwa Spring discharge data and NOx-T (total nitrate + nitrite) 1990-2019 and (B) linear correlation of discharge data and NOx-T.

2.8. Water Quality Data

Wekiwa Spring surface water quality data for the periods 1956-2020 and 1994-2019 were downloaded from the SJRWMD environmental database[7] and the Orange County Water Atlas online database[8], respectively. The sources of the data include SJRWMD, Watershed Information Network (WIN), and the STOrage and RETrieval (STORET), an FDEP database.

Water quality data were also obtained from the SJRWMD online database[9]. Shapefiles and spreadsheets of 2019 water quality sampling data for groundwater, springs, and surface water monitoring stations near Wekiwa Spring were downloaded and assessed for this project.

2.9. Relevant GIS Information

Land Use and Aerials, Soils, and Elevation

GIS layers for land use and aerials, soils, and elevations were obtained from the following databases: FDEP[10], NRCS[11], and Orange County, respectively. The NRCS soils GIS layer was used to display general runoff trends ranging from negligible to very high (Exhibit 6). Most study wells fall in low to very low soil runoff areas which corresponds to higher recharge rates as shown in Exhibit 3. Exhibit 7 shows a digital elevation map of the study area; shallow groundwater flow directions in the SAS layer have been observed to generally mirror surface topography in the study area (Section 2.3).

OSTDS GIS Layer

The 2017 OSTDS GIS layers from FDOH for Lake, Seminole, and Orange Counties were downloaded from an online FDOH database[12]. The known septic and likely septic areas are shown for the study area shown in Exhibit 8.

Biosolids or Other Wastewater Land Application Locations

GIS shapefiles for wastewater facilities and residual application sites were downloaded from the FDEP database[13]. The Wastewater Facilities shapefile includes 2016 data for Florida facilities that are Active, Closed but Monitored, or Under Construction and facilities that are unpermitted but require a permit. The Residual Application Sites shapefile has 2018 data for Florida sites where wastewater residuals are land applied. Exhibit 9 shows the locations of these sites within the study area; no residual application sites fall in the BMAP area.

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[7] http://webapub.sjrwmd.com/agws10/edqt

[8] https://www.orange.wateratlas.usf.edu/datadownload/Default.aspx

[9] https://www.sjrwmd.com/data/water-quality/#status-trends

[10] https://dep.state.fl.us

[11] https://www.nrcs.usda.gov/wps/portal/nrcs/detail/?cid=nrcs144p2_065038

[12] http://ww10.doh.state.fl.us/pub/bos/Inventory/FloridaWaterManagementInventory/

[13] https://floridadep.gov/water/domestic-wastewater/content/domestic-wastewater-biosolids

GIS shapefiles for reuse water service areas and destinations were downloaded from the SJRWMD database[14]. Exhibit 10 shows that none of the current study wells fall within reuse water application sites.

2.10. ECFTX Model

The East-Central Florida Transient Expanded (ECFTX) model (2019) and associated Model Documentation Report (Basso 2020) were reviewed for applicability to this project. ECFTX is a three-dimensional, eleven-layer, regional MODFLOW model covering 23,800 square miles of Central Florida. This model was developed to estimate the potential availability of groundwater that would impact future water supply and management strategies within the Central Florida Watershed Initiative (CFWI) area. One of the model benchmarks was to assess the sustainable limit of groundwater supplies, including predicting spring flows and associated aquifer water levels from baseline periods, including at Wekiwa Spring. The ECFTX model development included a collaborative effort amongst multiple state water management districts, FDEP, partner municipalities, public utilities, and other stakeholders within the planning area. The model completed a peer review process and was finalized in 2019.

Based on the above, the ECFTX model is deemed to be a suitable groundwater modeling tool to evaluate regional groundwater flow tracking within the Wekiwa springshed. Particle tracking and estimated dissolved nitrate fate and transport are discussed in Section 5.

[14] http://data-floridaswater.opendata.arcgis.com/datasets/reuse-destination-sjrwmd/data

3. GAP ANALYSIS – EXISTING DATA

Since 2017, Wood has been collecting groundwater samples from 22 existing wells and the Wekiwa Spring vent for standard physicochemical parameters. A subset of 12 wells and the spring vent were selected for stable isotope and wastewater tracer analysis based on higher nitrate-N concentrations (>1 mg/L). Based on availability at time of data review, this Gap Analysis includes quarterly sampling events from November 2017 to March 2020 conducted by Wood or other County consultants (Wood 2021).

3.1. Spatial Variability

This section examines isotope sample spatial variability within the springshed from various land uses, seasonality effects, groundwater units, and aquifer recharge. Observation of trends, or lack thereof, can be influenced by the size of the dataset; consequently, as more data are collected for this effort, the observations noted in this section may be revised.

3.1.1. Land Use

In Wood's most recent memo (September 2021), land uses for a 1-kilometer buffer around each well were determined and used to calculate average land uses among the study wells Based on Wood's desktop analysis, the predominant land use for the study area is residential which comprises approximately 55% of total land use for the analyzed area (Wood 2021). Suspected nitrate sources listed in Wood's analysis include fertilizers and OSTDS. The top six land use types for the study area are the following:

(1) 55.3% residential,

(2) 8.9% agriculture,

(3) 8.3% wetlands,

(4) 7.3% forested,

(5) 6.9% commercial, industrial, or institutional, and

(6) 4.7% recreational.

The remaining land use types made up less than 2% of the total analyzed area.

3.1.2. Seasonality

Orange County's fertilizer ordinance, adopted in 2017, restricts nitrate fertilizer application during the wet season from June to September. Water quality data and nitrate stable isotope data were explored for seasonal trends.

As stated previously, the Gap Analysis used data collected from November 2017 to March 2020 for analyses. An exception to this evaluation period was made for this seasonality exploration. For the entire set of available data collected from 2008 to 2021 and provided by the County to Drummond Carpenter, monthly average nitrate + nitrite concentrations were plotted and grouped based on aquifer unit (Figure 9). Seasonal trends in nitrate +nitrite concentrations are not evident in Figure 9; however, as more data are collected, seasonal trends may become more apparent.

There are several factors that may preclude observation of seasonal trends in nitrate including dataset size, variable fertilizer application frequencies and locations, use of irrigation in residential and golf course areas, travel time of leached nitrogen from application on lawn to groundwater, fluctuating denitrification rates, inconsistent travel paths from nitrate sources, and varying aquifer units (sampling depth). The lack of an observed strong seasonal trend of groundwater nitrate concentrations has been previously cited for the Wekiwa springshed. A 2014 study on nitrate in shallow groundwater in central Florida, including the Wekiwa springshed, found nitrate concentrations in groundwater were not significantly different between wet and dry seasons (Tucker et al. 2014).

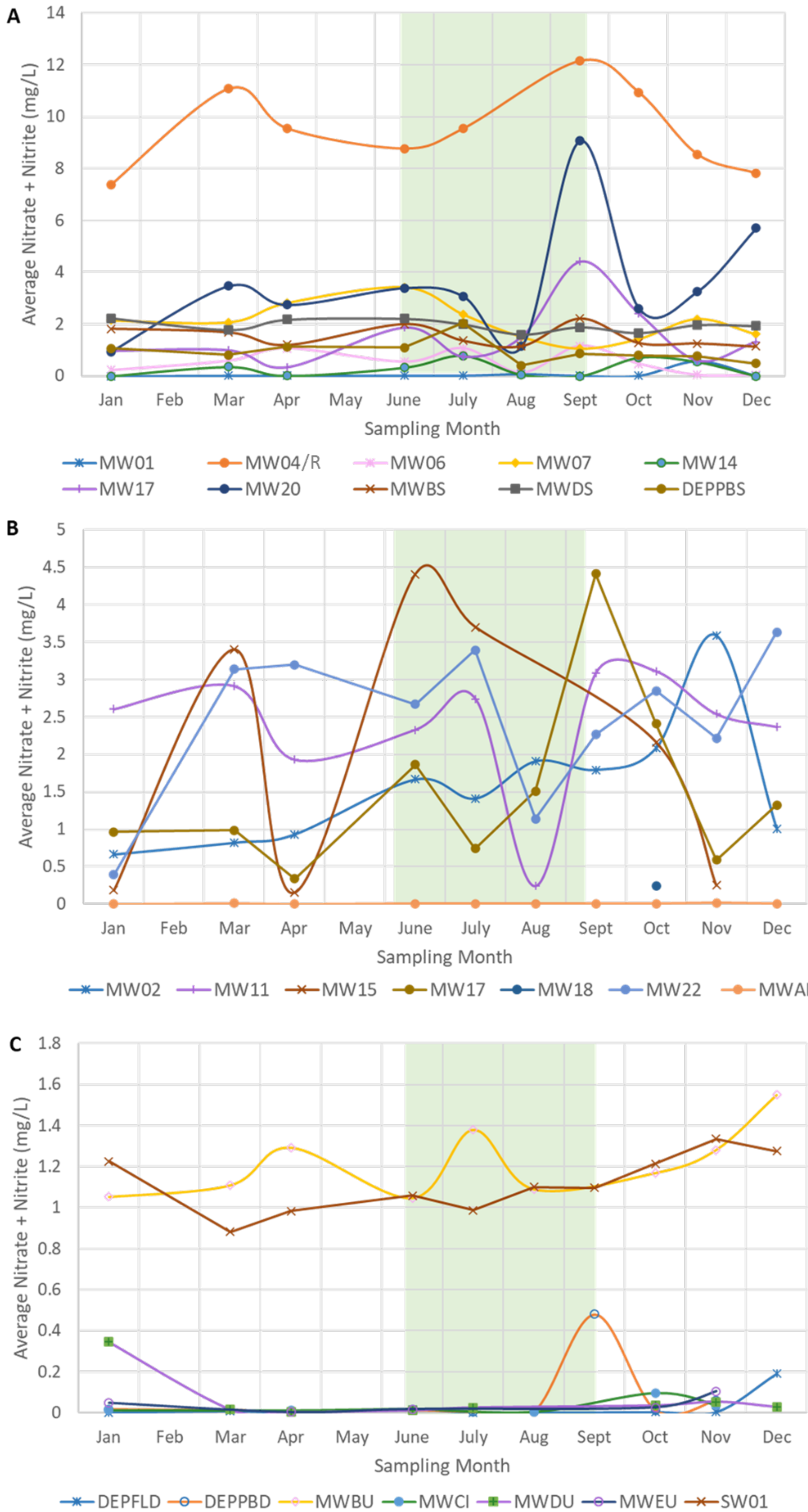

Figure 9. Monthly average nitrate + nitrite concentrations (mg/L) in (A) SAS wells, (B) IAS wells, and (C) Spring and UFA wells. Restricted fertilizer period shown as green block. (nitrate + nitrite measurements obtained from adjusted values in *Wekiva Data October 2008- June 2021 Master Data.xlsx*).

Trends with precipitation were explored by plotting monthly precipitation totals with nitrate-N concentrations for SAS wells. Nitrate-N concentrations measured at MW07 demonstrated some correlation with monthly precipitation totals (Figure 10). MW07 has the most complete dataset which may make this correlation more apparent compared to other wells with fewer data points.

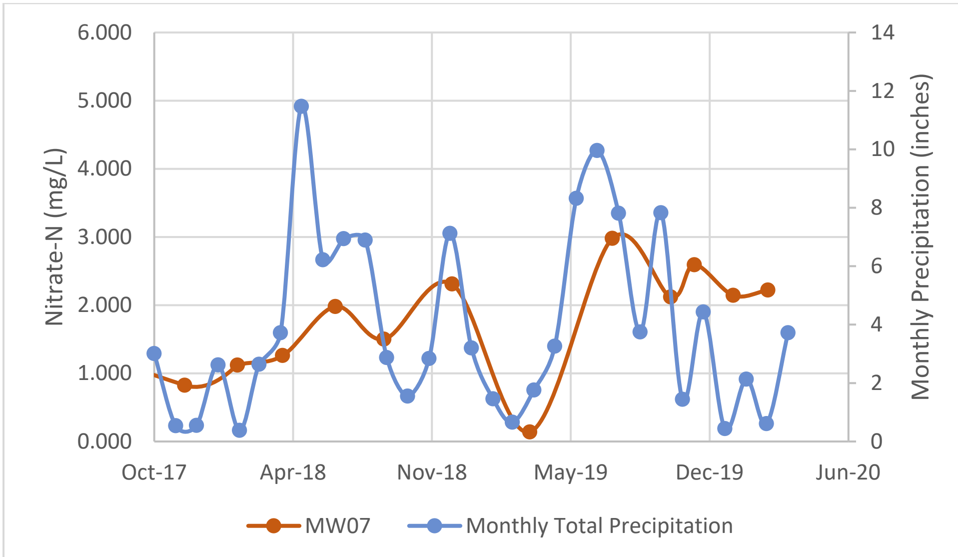

Figure 10. Correlation of nitrate concentrations and monthly precipitation totals at MW07 (Precipitation Data: SJRWMD, Rock Springs Station 11303088).

3.1.3. Groundwater Units

Most of the available isotopic data comes from wells screened in the SAS and IAS (Table 1). There are six SAS, four IAS, and one UFA monitoring well with isotopic data. Based on previous studies, Wekiwa Spring is primarily fed by the UFA (Toth 1999; Briggs et al. 2007; Harrington et al. 2010; FDEP 2015); however, isotopic values suggest the SAS and IAS may also contribute to the spring (Section 3.3). The available data indicate that generally, the UFA is characterized by lower DO, lower nitrate concentrations, and greater isotopic enrichment of nitrate compared to the SAS and IAS samples.

Table 1. Available isotopic data by monitoring zone (November 2017-March 2020).

Monitoring Zone	Available Isotopic Data	
	Monitoring Wells/Locations	Total Samples
SAS	6	36
IAS	4	25
UFA	1	6
Spring	1	5

3.1.4. Aquifer Recharge

Ten of 11 wells with isotopic data are in high recharge areas. The remaining well, XDEPPBS falls in a medium recharge area, and the spring vent is in a groundwater discharge area. The high recharge rates observed in the study area increase the vulnerability of groundwater to contamination. Accordingly, nitrate sources at the surface, or near surface, are more likely to reach groundwater, and eventually, Wekiwa Spring.

3.2. Sample Quantity and Density

This Gap Analysis contains data collected during sampling events from November 2017 to March 2020 which include a total of 72 isotopic samples. The number of available samples by well and season are shown in Figure 11. The frequency of isotopic sample collection varies by well, possibly due to the laboratory minimum nitrate detection limit for isotopic analysis, with the most samples (thirteen) collected at MW07 and the fewest (one) collected at MW02. This variation in sampling frequency can complicate observation of trends and comparisons among wells. Five wells have two or fewer isotopic samples; for wells with fewer samples, temporal variation and sample representativeness are difficult to assess.

To capture the fertilizer signature, there are more isotopic samples collected during the dry season and unrestricted fertilizer period, from October to May, than there are for the wet season. Roughly 70% of samples were collected during the dry season. However, if there is a considerable seasonal difference in isotopic signatures, this sample collection may skew source allocations to be more characteristic of the dry season.

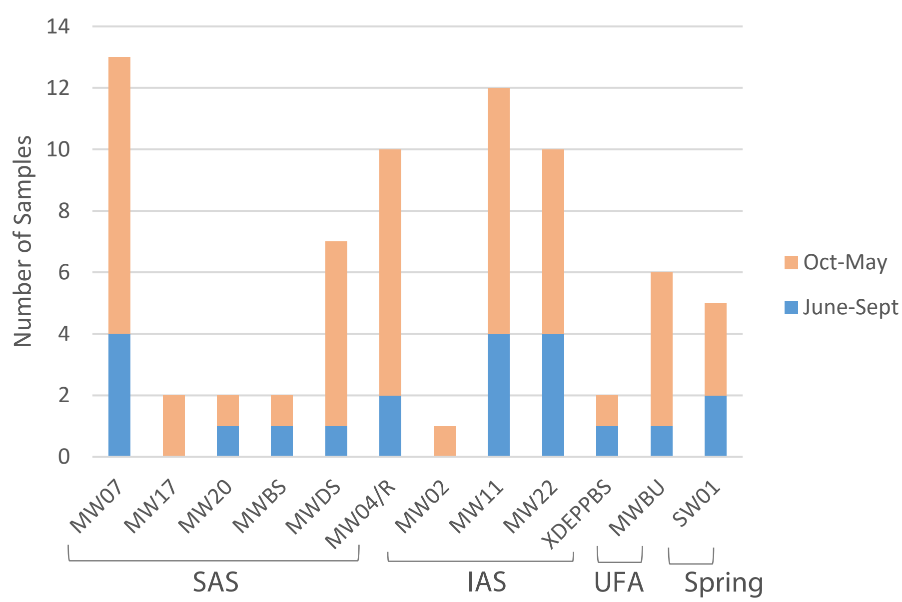

Figure 11. Available isotopic data by well (November 2017-March 2020).

3.3. Isotopic Analysis

Based on the data available from November 2017 to March 2020) the current nitrate sourcing study, UFA and Wekiwa Spring isotopic values are enriched relative to isotopic samples from the IAS and most samples from the SAS (Figure 12). A linear trendline fitted to available isotopic data has a slope of 1, which can be interpreted as evidence for denitrification based on strong covariation of $\delta^{15}N$: $\delta^{18}O$. UFA samples plot in the upper right corner, the farthest along the trendline, suggesting they have undergone the most denitrification.

Wekiwa Spring's isotopic values are less enriched compared to the UFA sampled well (MWBU). This is interesting because the groundwater reaching Wekiwa Spring from MWBU presumably has a greater potential for denitrification, which would further enrich the isotopes instead of depleting them. This finding suggests that the UFA region being sampled by the MWBU well is not fully representative of water being sampled at the Spring (assuming that the Spring is solely fed by the UFA). Wekiwa Spring water may be "younger" than that collected at MWBU, which is consistent with Toth and Fortich's (2002) finding that the Wekiwa Spring water is younger than the water sampled from within the springshed. Several possible explanations account for this, including:

(1) Nitrate levels and denitrification rates in the UFA springshed are not homogenous, and different regions may have different nitrate concentrations and associated isotopic enrichment.

(2) Conduit flow in the UFA springshed likely exists that may reduce denitrification in different regions by increased groundwater velocity toward Wekiwa Spring.

(3) The water being sampled at SW01 may not entirely be from the UFA. Surficial aquifer seepage and surface runoff into the spring may account for the SW01 sampled water composition, depending on the collection methodology and depth.

(4) Areas near Wekiwa Spring with high recharge rates may be mixing with the UFA prior to discharging.

The lack of additional UFA wells with isotopic data prevents further exploration of this.

The observed denitrification occurring in UFA samples is supported by dissolved oxygen (DO) measurements, which are represented by bubble size in Figure 12 with bubble size positively correlated with greater DO concentration. Generally, low concentrations of DO are expected before the process of denitrification becomes significant, though denitrification may take place in anoxic pockets within oxygenated sediment (Kendall et al. 2007). Analyzed UFA and Wekiwa Spring samples have DO values below 2 mg/L as well as a few IAS and SAS samples. The two SAS samples plotting near the UFA samples are both from MW17; the low DO observed in this well likely provides a suitable environment for denitrification that is not observed in the other SAS wells.

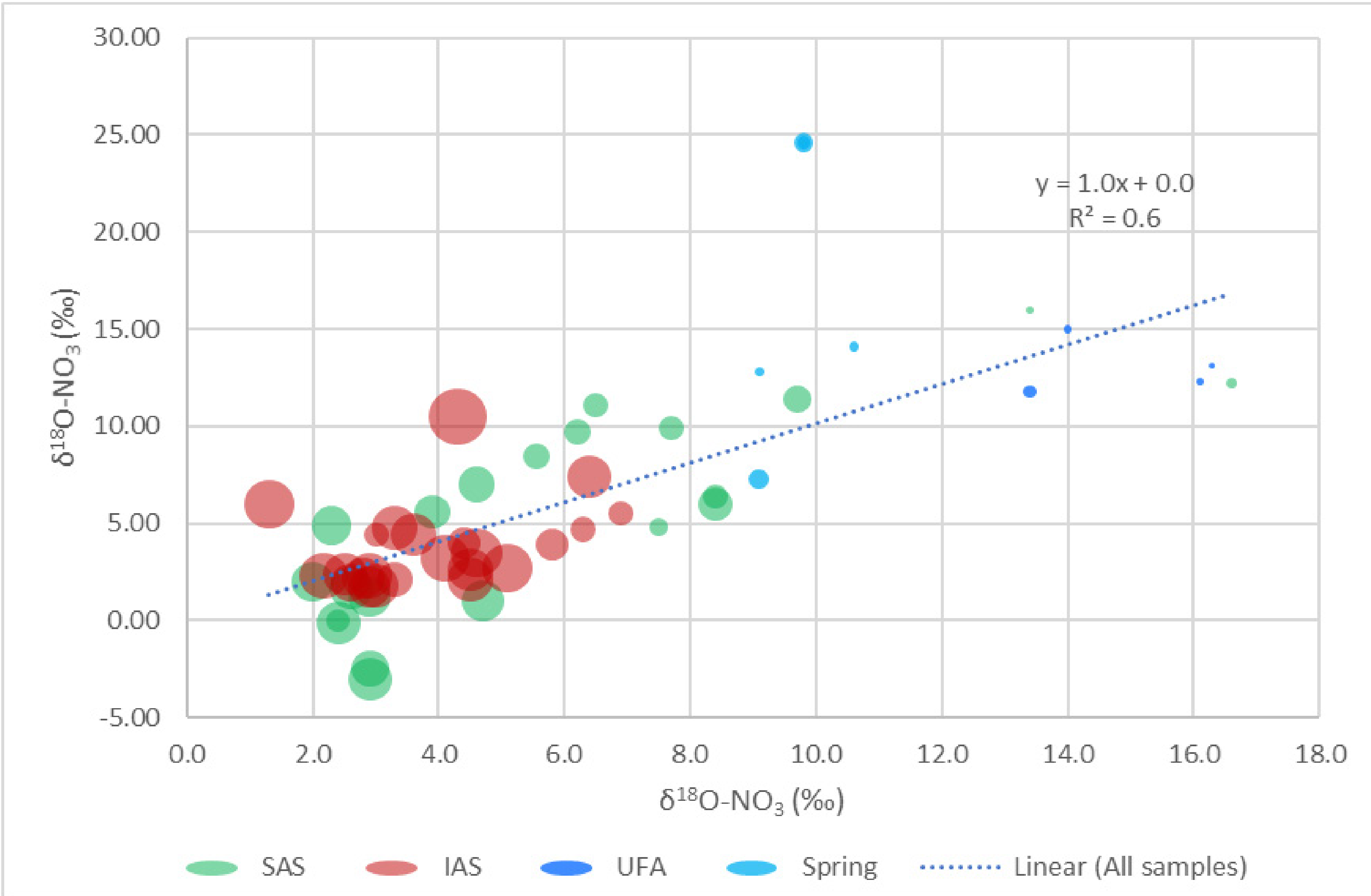

Figure 12. Nitrate Stable Isotope Samples by Monitoring Zone. Bubble size positively correlated with DO (mg/L). Larger bubble size represents greater DO concentration.

Principal component analysis (PCA) was used as another tool to investigate the role of denitrification in the samples collected for the current nitrate sourcing study. Optimal conditions for denitrification include the presence of denitrifying bacteria, reducing conditions related to low DO, and supply of carbon to act as electron donor source (Byrne et al. 2012). PCA was performed on a subset of data with a complete suite of measurements for 20 parameters. Strong correlation of $\delta^{15}N$ and $\delta^{18}O$; negative correlation of DO and $\delta^{15}N$ and $\delta^{18}O$; and negative correlation of total organic carbon (TOC) and $\delta^{15}N$ and $\delta^{18}O$ (assuming carbon is serving as an electron donor source) are all trends that provide evidence for denitrification (Figure 13).

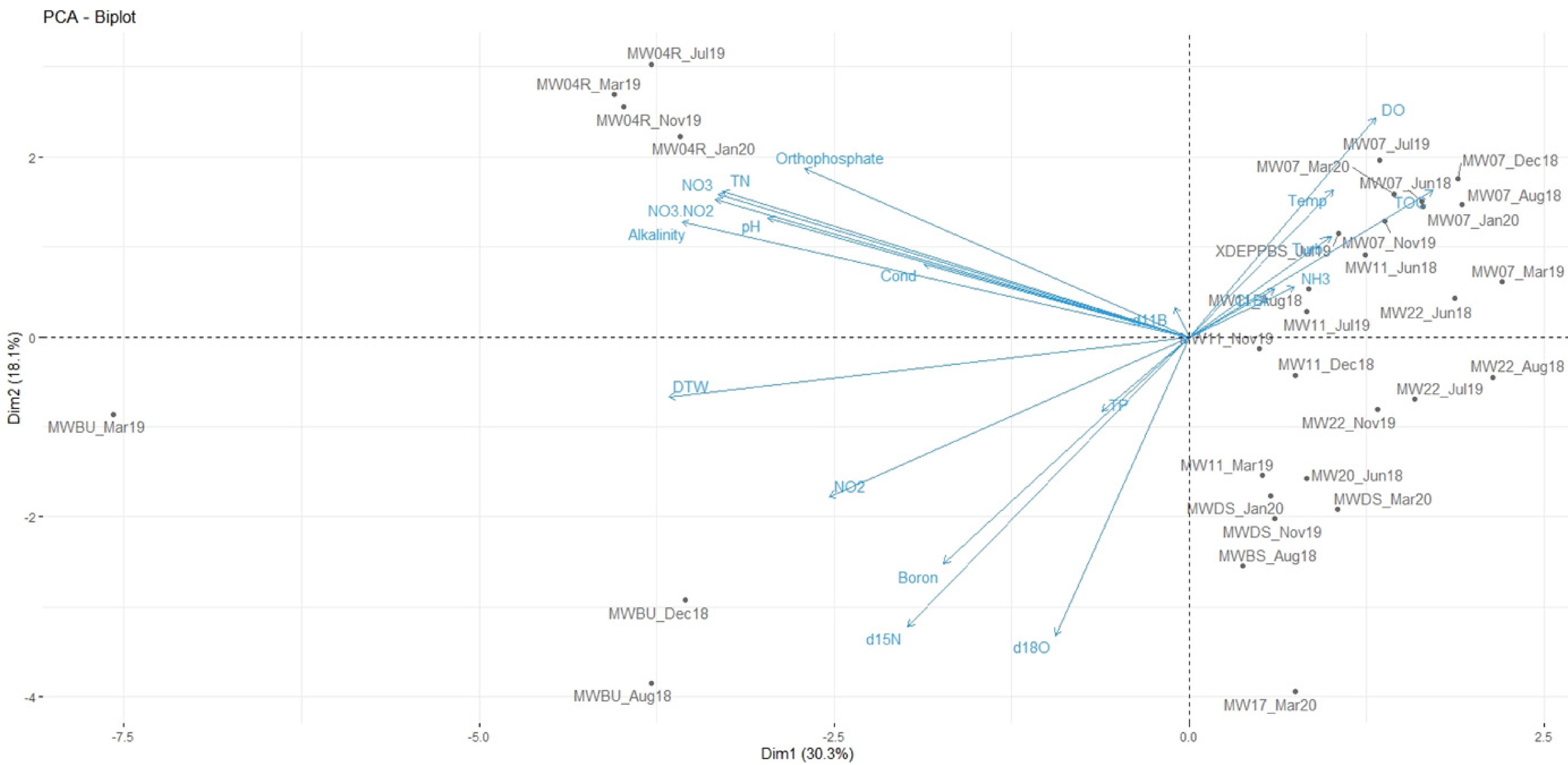

Figure 13. Principal component analysis on 32 samples and 20 parameters from the current nitrate sourcing study data.

3.4. Other Notable Observations

MWBS and MWBU are collocated wells south of the spring vent along a dry retention pond serving a golf course. MWBS is screened in the SAS and MWBU is screened in the UFA. Nitrate concentrations at MWBS and MWBU are consistent over time (Figure 14A). Other water quality parameters were not observed to exhibit the same consistency between wells. Expected SAS to UFA relationships were observed, such as higher conductivity and pH in MWBU relative to MWBS. Additionally, MWBU samples have lower DO concentrations and are isotopically enriched relative to MWBS samples (Figure 14B), which supports the observed trend that UFA samples have undergone greater denitrification. As denitrification occurs, the nitrate concentration would be expected to decrease in MWBU relative to MWBS, which for the most part, nitrate concentrations are marginally lower in MWBU. Currently, there are only two isotopic data samples for MWBS, and more data are needed to understand the relationship between these two wells and to better inform the inferred relationships between the SAS and UFA.

Additionally, MWBS and MWBU had significantly elevated nitrate-N concentrations measured in March 2019. In a small dataset, a group of uncharacteristically high values has the potential to skew results. A Grubbs' Test was performed for both MWBS and MWBU, which found both high values from March 2019 to be statistical outliers.

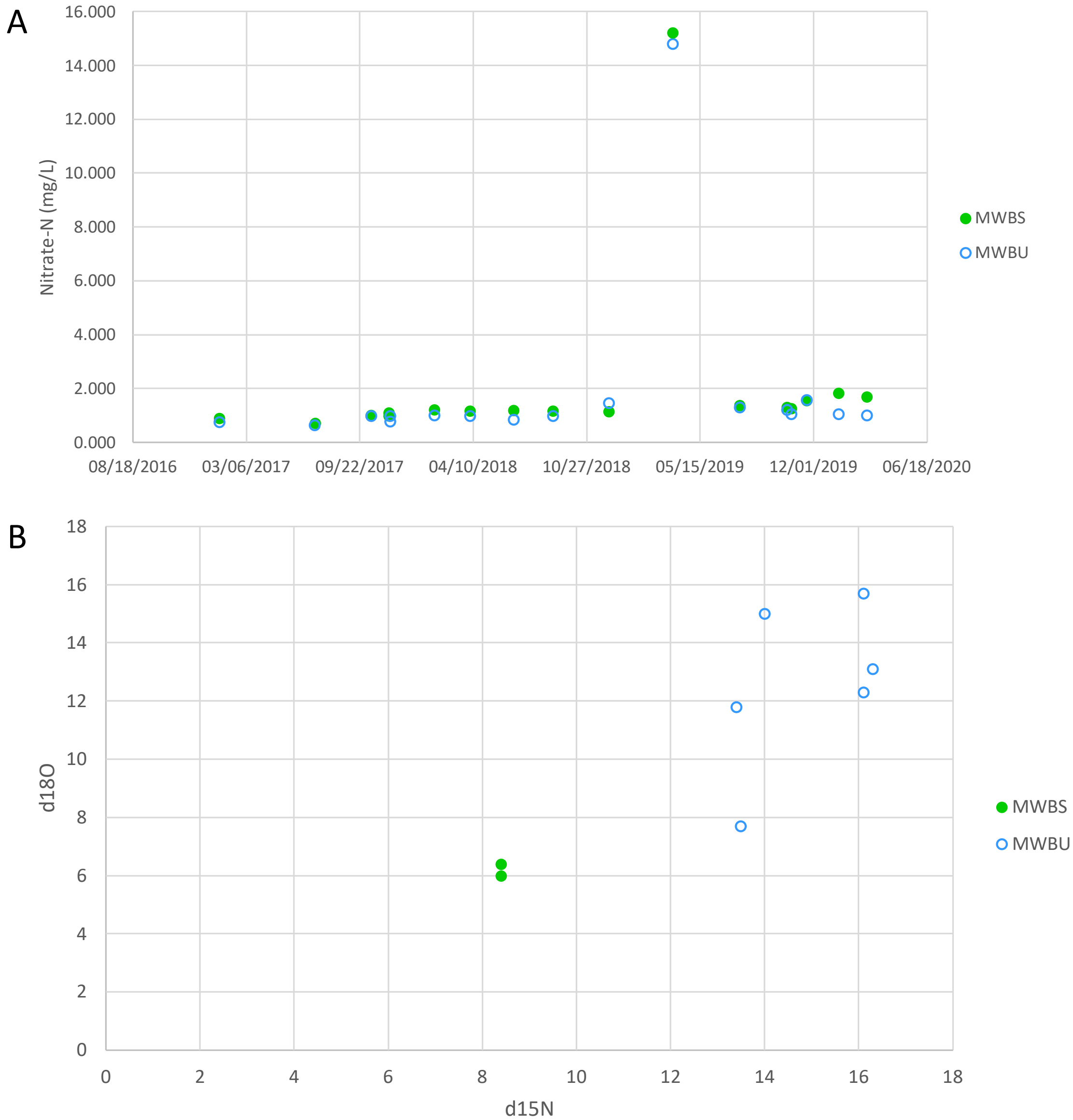

Figure 14. Comparison of MWBS and MWBU (A) nitrate-N concentrations and (B) nitrate isotopic values.

4. GAP ANALYSIS - ISOTOPIC MIXING MODEL

Isotopic mixing models have been developed for the Wekiwa springshed to help assess the relative proportion of various nitrate end member sources based on available isotopic and other groundwater monitoring information. These models can be particularly useful where isotopic data suggests mixed end member signatures with overlapping source distributions are present (e.g., sewage and fertilizer).

As mentioned in Section 2.5, Wood has completed a final isotopic mixing model which includes a denitrification end member. The results from this isotopic mixing model appear to be generally in agreement with the results from SIAR modeling performed by Drummond Carpenter as part of this Gap Analysis (see Section 4.2).

The Gap Analysis was performed with Wood's initial SIAR model (Wood 2020) as a reference to develop recommendations for strengthening results based on relevant studies and available data. This initial isotopic mixing model used literature source distributions from Clark and Fritz (1997) and Kendall (1998) which are assumed to be representative for the Wekiwa springshed, though source distributions can vary based on site specific parameters. Measuring site specific end member isotopic values may help further refine the source distributions to reduce some uncertainty in mixing model results. Additionally, the influence of denitrification was not considered in the initial mixing model. Because denitrification causes a shift in isotopic values as the nitrate pool becomes enriched in $\delta^{15}N$ and $\delta^{18}O$, not accounting for the shift produced by denitrification may cause the sewage and manure sources of nitrate to be overestimated. Wood acknowledged both source distribution uncertainty and denitrification effects on their model results in their technical memorandum (Wood 2020) and have since updated their isotopic mixing model to include denitrification and revised source distributions. For the Wood SIAR model, "uninformative" priors were assumed such that all nitrate sources could contribute equally.

4.1. Recommendations for the Isotopic Mixing Model

SIAR model results can be improved by considering and reducing the sources of uncertainty in the model. There are three key sources of uncertainty:

(1) source distributions,

(2) biogeochemical processing (i.e., denitrification), and

(3) sample size per well.

Most studies rely on literature defined source distributions. However, isotopic signatures of various nitrate sources have been observed to differ due to variations in geology, time of year, climate, and biogeochemical processes (Finlay et al. 2009; Xue et al. 2009; Zhang et al. 2019). Consequently, source distributions can be influenced by site specific conditions causing source distributions found in literature to have broad, overlapping ranges. Recommendations to develop localized source distributions are provided in Section 4.4.

Another suggestion to reduce uncertainty in the model involves the removal of the soil end member, which significantly overlaps with the NH_4^+/Urea fertilizer and sewage/manure end members and is not likely a major contributor of total nitrate relative to the other end members. Removing the soil end member is supported by relevant published work (Canion et al. 2020). Additional rationale stems from the magnitude of measured nitrate concentrations in study wells relative to the expected concentrations of soil nitrate. Soil nitrate is the 'background' or natural nitrate that leaches from soil to groundwater. In karst areas of north and central Florida, background concentrations of soil nitrate are estimated to be less than 0.02 mg/L in groundwater (Howard T. Odum Florida Springs Institute[15]). Average total nitrate-N measured in study wells with isotopic data ranges from 1 to greater than 10 mg/L, making soil nitrate concentrations essentially negligible. This finding is consistent with well BW02 (SAS), which is considered a background well located within the Wekiwa Spring State Park that that likely experiences minimal anthropogenic impact. BW02 has a median nitrate-N concentration less than 0.01 mg/L, which is consistent with an insignificant soil nitrate source. Refer to Exhibit 5 for a depiction of well BW02.

As discussed in Section 2.2.1, fractionation factors were developed to mimic trophic enrichment processes and are not representative of the denitrification process; therefore, fractionation factors were set to zero. Still, strong evidence of denitrification exists in the samples and should be accounted for in the SIAR model to achieve more realistic results.

Additionally, the greater the sample size per well, the more likely the collection of isotopic data points capture temporal variation and are representative of conditions at the well. Currently, some wells included in the SIAR model have two or fewer isotopic data points. The limited isotopic data for these wells may not be representative which creates uncertainty in the source allocations. The SIAR modeled consistently assigned roughly equal contributions of each source to these wells with limited data, likely indicating the model may benefit from more data per well. Collecting more isotopic data per well will improve confidence in representation of each well.

Finally, as stated in the Wood (2020) technical memorandum, the SIAR modeling can be improved using prior distributions. The current gap analysis did not include a review of the impact of SIAR results using priors, but recent studies completed by Canion et. al (2020) illustrate the potential benefit of incorporating *a priori* information to guide the Bayesian model's source proportion determinations.

4.2. SIAR Modeling Completed for Gap Analysis

Additional SIAR modeling was performed by Drummond Carpenter as part of the gap analysis to explore the impact of enacting recommendations discussed above. Seventy-two isotopic data points collected from 12 sampling locations (11 wells and the spring vent) as part of the current nitrate sourcing study from November 2017 to March 2020 were included in this assessment.

Consistent with recommendations in Section 4.1, the soil end member was removed from SIAR. Remaining source distributions were kept consistent from preliminary modeling completed by Wood (2020). The source distributions are shown in Table 2. The final revised isotopic mixing model created by Wood includes slightly different source distributions from those listed in Table 2 (Wood 2021). The SIAR modeling performed for the Gap Analysis was not updated to reflect the updated source

[15] http://www.lake.wateratlas.usf.edu/upload/documents/Springs-Facts-FSI-012414.pdf

distributions used in Wood's 2021 model as the results should still be comparable between the two models.

Additionally, Drummond Carpenter proposed a novel approach to quantify uncertainty caused by denitrification in the SIAR modeling. A denitrification 'end member' was created based on the observed trajectory of isotopic enrichment exhibited by the samples. This approach was based on related published work by Divers et al. (2014). Large standard deviations were assigned to the denitrification end member to acknowledge the uncertainty as denitrification rates were not measured in this study (Table 2). The denitrification end member allows the SIAR model to assign some portion of enriched samples to denitrification that may have been assigned to sewage/manure without consideration of denitrification.

Table 2. SIAR source distributions for selected nitrate sources (modified Table 7 from Wood 2020).

Source	$\delta^{15}N$ (‰) Mean	$\delta^{15}N$ (‰) Standard Deviation	$\delta^{18}O$ (‰) Mean	$\delta^{18}O$ (‰) Standard Deviation
NH_4^+/Urea Fertilizer	1.00	1.50	3.00	2.50
Wastewater, Septic and Manure	13.50	3.25	2.00	2.00
NO_3^- Fertilizer	2.50	1.25	21.50	1.75
'Denitrification'	25.00	5.00	25.00	5.00

The source distributions in in Table 2 are shown in Figure 15 along with the 72 isotopic data points included in Drummond Carpenter's SIAR model. Some samples fall within the NH_4^+/Urea Fertilizer source distribution box. The remainder of the samples fall outside of the defined source distribution boxes but generally fall along the linear trendline, which suggests the process of denitrification could be altering the nitrate isotopic signatures from their original source signature.

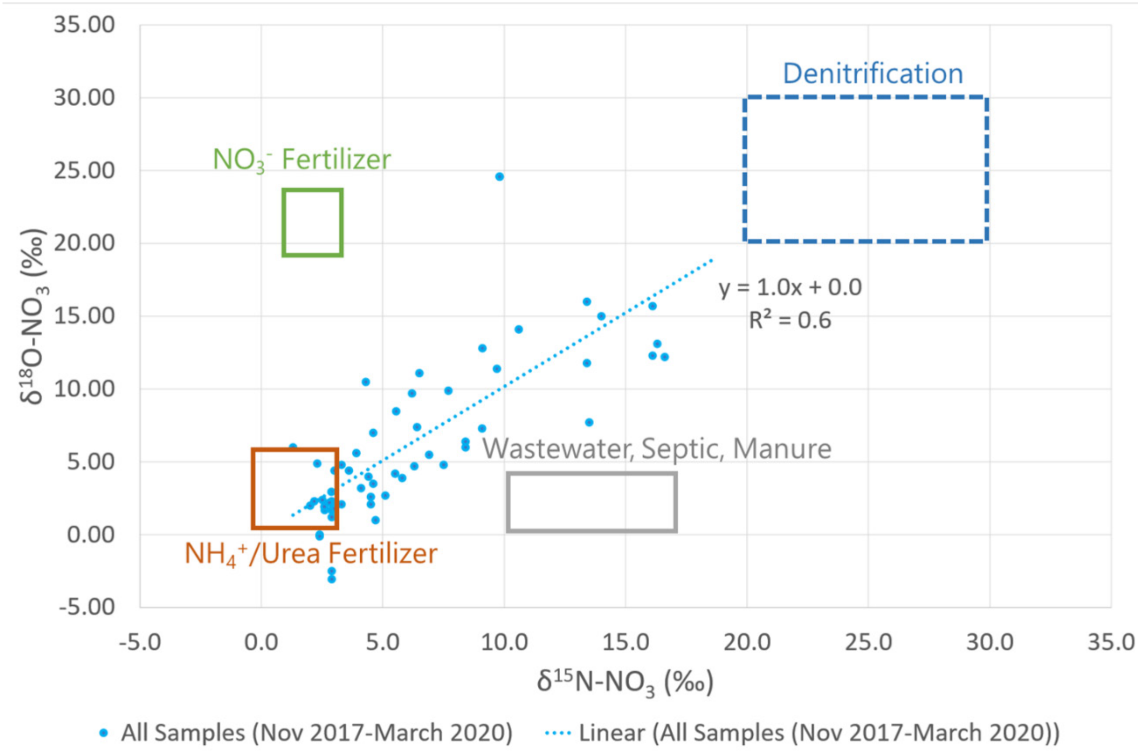

Figure 15. Isotopic Data and End Members included in Isotopic Mixing Model.

SIAR modeling was performed with the data grouped by well, resulting in relative nitrate source allocations for each well. Interpretation of source allocations for each well should consider the frequency at which each well was sampled. One well, MW07, has as many as 13 isotopic data points collected throughout the calendar year; the source allocations for this well are likely to be more representative and capture more temporal variation compared to source allocations calculated for a well with only a single isotopic data point, such as MW02.

SIAR modeling estimated fertilizers were the top contributors to total nitrate in 10 of the 12 sampling locations. Exhibit 11 shows average nitrate source allocations by well as pie charts. The pie charts were created using average modeled relative percent contribution from each of the nitrate sources. While the pie charts are an effective way to convey nitrate apportionment by well, they do not display the uncertainty associated with SIAR results. Therefore, boxplots of the SIAR results are shown in Figure 16 for each sampling location.

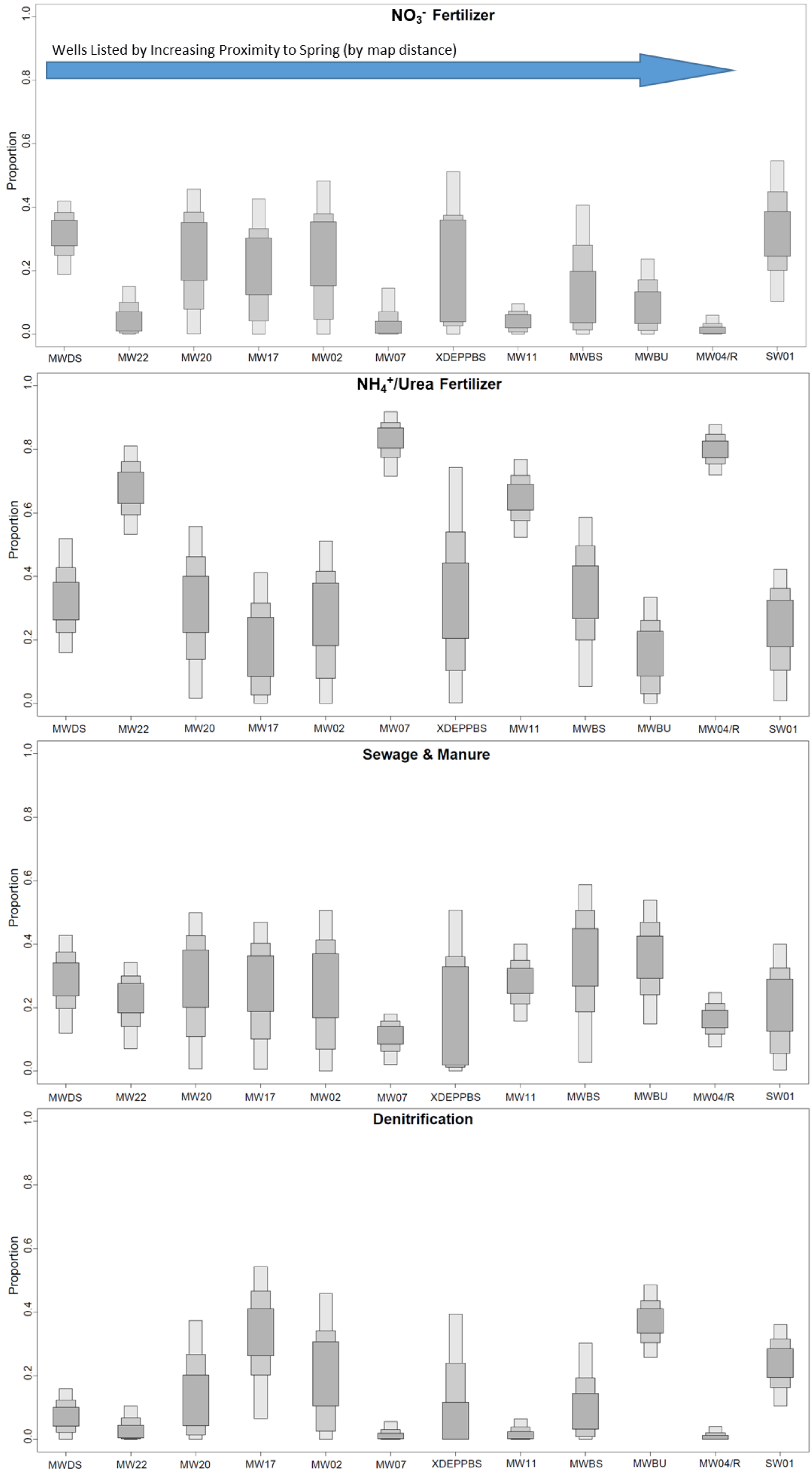

Figure 16. SIAR nitrate proportions by source by well.

From Drummond Carpenter's SIAR modeling, MW22 (IAS), MW07 (SAS), MW11 (IAS), and MW04/R (SAS) have notably elevated nitrate contributions from NH_4^+/Urea fertilizer. MW17 (SAS), MWBU (UFA), and SW01 (Spring) show greatest proportions of denitrification which are consistent with findings reported in Section 3.3 and Figure 12. Wells with large uncertainties across all sources coincide with wells with limited datasets (two or fewer isotopic data points) including MW20, MW17, MW02, XDEPPBS, and MWBU.

Boxplots from SIAR results can also be used to examine nitrate sources one well at a time. MW04/R is the closest in proximity to the spring and has the highest observed nitrate concentration of the monitoring wells, making it a high interest well. SIAR estimates that approximately 80% of total nitrate at MW04/R is originating from NH_4^+/Urea fertilizer (Figure 17).

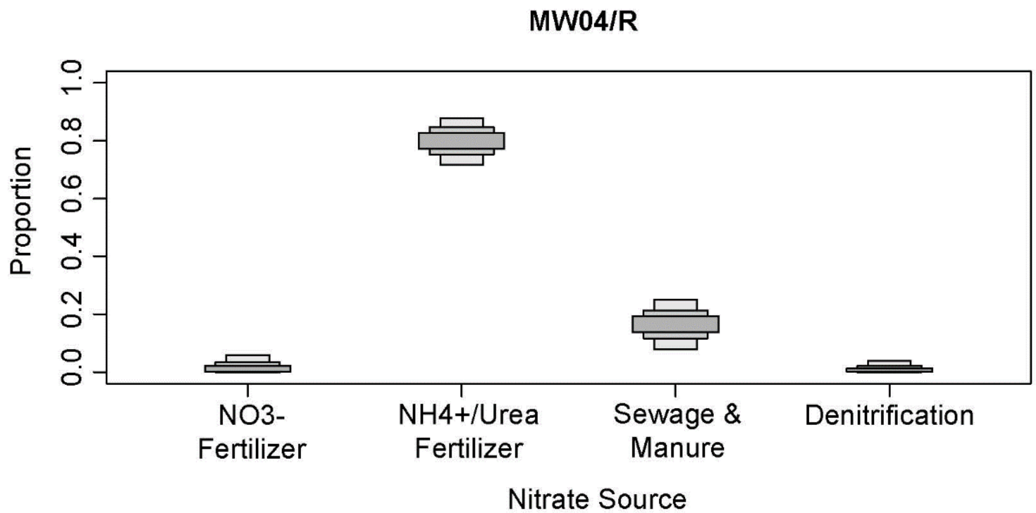

Figure 17. MW04/R nitrate source proportions by SIAR.

Model results indicating fertilizer is a dominant source is supported by similar studies conducted within the Wekiwa basin. Specifically, Canion et al. (2020), also using a Bayesian stable isotope mixing model, found mean fertilizer contributions to nitrate ranged between 40% and 100% in residential wells located in central Florida, including the Wekiwa basin. These studies support the potential positive impacts of fertilizer reduction practices on total nitrate loading within the Wekiwa PFA. Still, the importance of nitrate reduction strategies aimed at other identified nitrate sources, such as septic systems, should not be overlooked.

4.3. Comparison to BMAP Nitrate Allocations

Based on the NSILT model developed for the Wekiwa BMAP, the following were the top three contributors to the total nitrogen loading to groundwater:

(1) fertilizers (sum of urban turf grass, farm, sports turfgrass fertilizers) 45%,

(2) OSTDS contributing 29%, and

(3) wastewater treatment facilities contributing 16% (FDEP 2018).

The percent contributions for all suspected sources are shown in Figure 4. Restoration approaches of the BMAP include restrictions on the installation of new OSTDS, improvements to existing OSTDS, monitoring credit systems for fertilizer application, and effluent standards for wastewater treatment facilities.

Similar to the BMAP NSILT findings, the SIAR modeling performed by Drummond Carpenter also found fertilizers to be the top contributor to nitrate, at the sampling locations, followed by septic and manure sources. A slightly greater proportion of total nitrate was attributed to fertilizers by the SIAR model compared to the BMAP NSILT, which may be a function of the well network used in the SIAR model. The BMAP NSILT results were based on the entire Wekiwa BMAP whereas the well network used in the SIAR model was entirely within the Wekiwa PFA and primarily installed near residences on sanitary sewer to support a targeted study aimed at exploring the impact of fertilizer application and seasonality. Installing new well clusters in septic areas and incorporating their isotopic data into SIAR may increase the number of locations where septic systems are a dominant source.

4.4. Source Distribution Recommendations

In the SIAR model, assigned source distributions are relied on to estimate relative contributions of individual nitrate sources to the waterbody of interest; therefore, the performance of the model depends on the assumption that the source isotopic signatures are representative. The literature review demonstrated source distributions for common nitrate sources have broad ranges and can vary based on site specific factors. Based on the literature review, advice from isotope laboratories, and review of the current study's mixing model, developing more localized source distributions for use in the SIAR model is recommended.

End member sampling of suspected nitrate sources (i.e., direct sampling of source products, such as raw septic water or fertilizer) within the Wekiwa springshed can be used to create localized source distributions. The isotopic signatures measured from end member sampling can be compared to literature values from similar studies and used to estimate source distributions. The following recommendations for end member sampling are provided:

- For all end members, the samples are recommended to be filtered down to 0.2 micrometers (µm) and preserved through appropriate methods to avoid microbial changes to the sample post-collection.
- Septic sampling – Sampling raw water from a septic tank and drainfield is recommended.
- Reclaimed water – Sampling raw water from reclaimed water is recommended.
- Fertilizer – There are three suggested options for collecting a fertilizer sample.
    - Mixing fertilizer and deionized water to create a sample. Depending on the fertilizer, this method may not produce the most representative results because there is not the opportunity for nitrification of the fertilizer in soil which converts ammonium to nitrate. Nitrification is a type of nitrogen isotopic fractionation (like denitrification) that alters isotopic proportions.

  - An alternative, though, more involved method, is to collect runoff from a recently fertilized and controlled field, which may be more indicative of the fertilizer signature measured by isotopic sampling.
  - A final option for collecting a fertilizer sample is to install lysimeters in a residential lawn.

5. GAP ANALYSIS - FATE AND TRANSPORT

Understanding groundwater movement is critical in assessing nitrate contamination in the Wekiwa springshed and is considered a significant gap in the general knowledge of Wekiwa nitrate transport. Drummond Carpenter therefore applied ECFTX to simulate groundwater flow within the Wekiwa springshed to better understand and visualize potential nitrate migration within the Wekiwa PFA. Specifically, the three-dimensional model was used to estimate the Wekiwa springshed areal extent, groundwater flow direction, velocity, and travel time. Results from ECFTX were applied in conjunction with Earth Volumetric Studio (EVS)[16] software to conceptually depict how nitrate applied within the Wekiwa springshed may reach the Wekiwa spring vent.

5.1. ECFTX Model

ECFTX is a three-dimensional groundwater MODFLOW-based model that incorporates over 23,000 square miles of model domain, including the Wekiwa springshed. The model has a horizontal computational grid resolution of 1,250 feet (ft) by 1,250 ft and includes eleven vertical layers to represent the hydrogeologic units from land surface to the base of the Floridan aquifer system (FAS). The thickness of the layers varies based on the position within the model grid and the hydrogeologic unit that each layer represents (Basso 2020). Refer to Figure 18 for the model's hydrostratigraphic conceptualization. For this assessment, Drummond Carpenter used the model to perform steady-state simulations, which were based on flow conditions as of 2003. Because greater spatial resolution was desired for this assessment, Drummond Carpenter revised the ECFTX model by increasing the horizontal cell resolution to 125 ft x 125 ft within the Wekiwa area of interest.

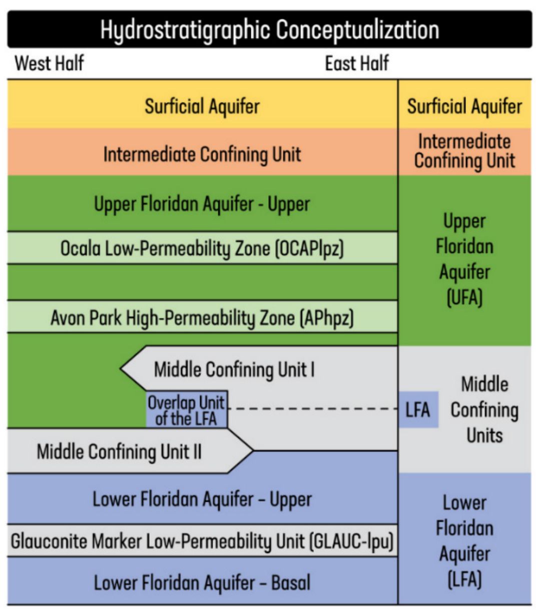

Figure 18: ECFTX hydrostratigraphic characterization (from Basso 2020).

[16] https://www.ctech.com/

Five separate model runs were performed to assess the sensitivity of the model to wet and dry periods as well as varying Lake Apopka lake levels, which were assumed to be important variables with a high potential for change from year to year that may affect model results. These model runs are summarized below:

(1) Baseline model with no changes (only increased spatial grid resolution)

(2) Alternate Scenario 1 - Baseline model with increased recharge of 50% (indicating an extremely "wet" period)

(3) Alternate Scenario 2 - Baseline model with decreased recharge of 50% (indicating an extremely "dry" period)

(4) Alternate Scenario 3 - Baseline model with Lake Apopka at historic high-water level (68 feet NAVD88)

(5) Alternate Scenario 4 - Baseline model with Lake Apopka at historic low water level (62 feet NAVD88)

5.1.1. ECFTX Model Particle Tracking

Particle tracking using MODPATH was the primary tool to analyze the model results regarding groundwater flow path and velocity. Particle tracking allows the user to specify any number of points in the three-dimensional model and track its associated groundwater travel path both forward in time (forward particle tracking) or backward in time to its point of origin (reverse particle tracking). The below sections represent the ECFTX model findings based on the Baseline model, with discussion on the variability of the results from the limited sensitivity model runs described above.

5.1.1.1. Groundwater Flow Direction and Springshed Areal Extent

Using the baseline model, reverse particle tracking around the Wekiwa Spring vent was initially conducted to assess the modeled region that is predicted to flow to the spring (under 2003 steady-state flow conditions). The reverse particle tracking included placing 300 virtual particles spaced around the spring in a grid, with corresponding particles at each of the top 5 layers (1,500 particles total) as shown in Exhibit 12. Forward particle tracking for the entire BMAP area was performed by placing particles at a 1 square mile grid within the SAS layer. The results are shown in Exhibit 13.

Per the exhibits, it is evident that the Wekiwa springshed covers a large area primarily southwest and west of the spring, including portions of Lake Apopka and farther west into areas of Lake County and south towards the Horizons West region of Orange County. These limits are in general agreement with previous modeling efforts for the spring. Under the scenario posed, areas south and southeast of the intersection of South Semoran Boulevard and South Orange Blossom Trail are predicted to not flow toward Wekiwa Spring but instead bypass to the east and continue north into Seminole County, ending in the spring cluster associated with Starbuck, Sanlando, and Palm springs or bypassing the BMAP area altogether. This potential Wekiwa bypass area includes several monitoring wells used in this study, including MW10, MW14, MW15, MW20, and MW22. If the ECFTX model (2003 steady-state flow) represents typical conditions, then some of the groundwater within the Wekiwa PFA may not discharge to the Wekiwa BMAP area, and some of the monitoring wells that have been sampled and analyzed for Wekiwa Spring purposes, may not consistently drain to the spring. However, it is noted that aquifer flow frequently changes, and transient flow conditions are expected. Additionally, large portions of Lake Apopka are not predicted to flow to Wekiwa Spring, consistent with previous SJRWMD groundwater modeling and particle tracking efforts.

The particle tracking results indicate that groundwater outside of Wekiwa Spring State Park generally flows downward from the SAS layer to the IAS and then into the UFA. The area within and near Wekiwa Spring State Park experiences upward groundwater movement, most notably to Wekiwa Spring and Rock Spring. Most of the lateral movement of groundwater occurs in the UFA, simulated by model layers 3, 4, and 5. Groundwater was not predicted to travel far in layer 4, with the more porous and highly conductive limestone layers represented by 3 and 5 associated with most of the lateral travel. In model layers 1 and 2 (SAS, IAS, respectively), the SAS layer has most of the lateral groundwater movement, though it is generally localized to several hundred feet before recharging into the IAS layer. The largest SAS travel is modeled to occur around Wekiwa Golf Club, with modeled flows of approximately one mile before recharging into the IAS. Near the spring vent, groundwater tends to stay within the SAS and migrate laterally until reaching the spring, spring run, or other surface water body within the State Park.

For the alternative scenarios, varying the lake levels in Lake Apopka (Alternate Scenarios 3 and 4) did not appear to have a significant impact on the model results, with the overall spring flow extent and groundwater flow direction generally unchanged. For Alternate Scenario 1, increasing the recharge resulted in the Wekiwa springshed shifting slightly to the northwest, capturing greater areas north of Zellwood. For Alternate Scenario 2, the reduced recharge resulted in the most significant change by pushing the springshed more south and slightly east, with most of the area around Zellwood being removed from the springshed.

5.1.1.2. Wekiwa Spring Flow

In the ECFTX model, Wekiwa Spring was modeled as a drain type boundary condition which predicts discharge based on the difference between the predicted head and the specified drain elevation. For the baseline and alternative scenarios, the discharge was predicted as presented in Table 3.

Table 3: ECFTX Simulated Discharge at Wekiwa Spring

Scenario	Flow (ft3/sec)
Baseline	71
Alternate Scenario 1 Recharge +50%	83
Alternate Scenario 2 Recharge -50%	56
Alternate Scenario 3 Lake Apopka 68 ft	71
Alternate Scenario 4 Lake Apopka 62 ft	71

As seen in Table 3, the baseline scenario is within the expected range of discharge based on the historic Wekiwa Spring discharge measurements depicted in Figure 7, with the Alternatives 1 and 2 results indicating increased and decreased discharges at the spring, which would be anticipated during extreme wet and dry periods, respectively. A historical maximum spring flow of approximately 92 cubic feet per second, historical minimum spring flow of approximately 49 cubic feet per second, and an average spring flow of approximately 62 cubic feet per second are documented, which reasonably compares with Alternatives 1 and 2 and baseline simulation results. Alternatives 3 and 4 associated with Lake Apopka stages did not significantly impact the model discharge results at Wekiwa Spring. Based on the above, the ECFTX model appears to reasonably estimate the flow at Wekiwa Spring.

5.1.1.3. Groundwater Travel Time

Forward Particle Tracking

Forward particle tracking for the baseline model scenario was analyzed within a subset of the Wekiwa springshed associated with the area modeled to discharge to Wekiwa Spring within the PFA. Particles were placed on a grid with a spacing of 1,250 feet x 1,250 feet and forward tracked until they reached a discharge point or boundary condition. The particles that did not outfall to Wekiwa Spring via the UFA, such as those reaching a water supply well or near-spring regions, were removed. A total of 732 forward tracking particles were within this area. Particles were released from the top of the water table in the SAS layer.

The total travel time for each particle to reach Wekiwa Spring after vertically passing through underlying groundwater layers was assigned as the value to each originating grid point. The grid points were then interpolated using a nearest neighbor GIS interpolation procedure to create a travel time raster image, representing a spatial map of the modeled time it takes groundwater to travel from its point of origin to Wekiwa Spring. Refer to Exhibit 14.

From the figure, the predicted groundwater travel times ranged from approximately 190 days (0.52 years) to over 11,000 days (greater than 30 years). The median travel time value was 706 days (approximately 1.9 years).

Trends in groundwater travel time (based on steady-state simulations) are presented below:

- Generally, the areas north of State Road 436, southwest of Wekiwa Spring have a short groundwater travel time, on the order of 200-500 days. A majority of the wells used in this study are located in this area.
- Portions of South Apopka east of State Road 429 and west of State Road 451 have relatively short travel times on the order of 400-700 days.
- A small area north of Zellwood north of Ponkan Road on both sides of State Road 429 also has relatively short travel times in the range of 500-700 days.
- Other areas experience much longer groundwater travel times, generally greater than 1,000 days. These areas are located along the western end of the PFA, as well as the region south of Zellwood. A pocket of slower groundwater travel time in South Apopka is also present.

The median time for groundwater to travel through the SAS and IAS layers into the UFA is 373 days, with the travel time in these layers sometimes exceeding the travel time in the UFA, even though groundwater travels much farther in the UFA than in the upper layers. This illustrates the importance of recognizing the upper layer travel times as potentially adding time for recharge to occur prior to reaching the faster-moving UFA. The dye tracer tests performed as part of FDEP's PFA development did not account for this additional groundwater travel and therefore likely underestimates the time it takes for a nitrate source that is applied to the land surface to travel to Wekiwa Spring.

Reverse Particle Tracking

Reverse particle tracking from all 1,500 reverse particles around Wekiwa Spring were compared for the baseline scenario, as well as the Alternative Scenario 1 (+50% recharge) and Alternative Scenario 2 (-50% recharge). The median travel time for all particles by scenario is provided in Table 4.

Table 4: Reverse Particle Travel Time

ECFTX Model Scenario	Median Travel Time (days)
Baseline Model	1,395
Alternate Scenario 1 Recharge +50%	774
Alternate Scenario 2 Recharge -50%	3,549

From Table 4, the ECFTX model travel time to Wekiwa Spring is sensitive to recharge, suggesting that during wet years travel time is decreased and during dry years travel time may increase. This sensitivity to recharge alters the potential for denitrification to occur within the springshed, consistent with the findings from the Albertin et al. (2012) denitrification study.

Exhibits 15 and 16 show the reverse particle tracking results for time periods of 1 year and 3 years from Wekiwa Spring for the baseline model. These exhibits illustrate the paths the virtual particles traveled to Wekiwa Spring, including hydrogeologic layers. Note that only reverse particles shown ending in the SAS layer (orange line segments) can reasonably be expected to cause water quality impact to Wekiwa Spring in the timeframe shown.

Dye Tracer Comparison

The ECFTX model is an equivalent porous medium model that represents the complex karst features of the UFA using spatially and volumetrically averaged hydraulic properties in model cells (Basso 2020). To assess the accuracy of the ECFTX model, an additional forward particle tracking analysis was performed on the baseline model to compare simulated travel times with those determined by tracer tests performed at Rock Springs and Wekiwa Spring by FDEP. To simulate the Wekiwa Spring dye tracer test, a virtual particle was placed in layer 3 to represent tracer release from well XDEPPBD, which is screened approximately 200 ft below land surface within the UFA. To simulate the Rock Springs dye trace test, a virtual particle was placed in layer 3 to represent well XDEPFLD, which is screened approximately 100 ft below land surface within the UFA. Using the ECFTX model, flow was simulated under the baseline conditions, and particle tracking results were used to estimate travel times from the wells to their corresponding springs for comparison against the travel times determined in the dye tracer tests. Travel times from the ECFTX simulation and the dye tracer tests are presented below in Table 5.

Table 5: Dye Tracer and ECFTX Comparison Table

Test	Approximate Travel Time (days)
FDEP Wekiwa Spring Dye Tracer Test (XDEPBD)	50
FDEP Rock Springs Dye Tracer Test (XDEPFLD)	7
ECFTX Wekiwa Spring Particle Tracking (XDEPBD)	25
ECFTX Rock Springs Particle Tracking (XDEPFLD)	38

The ECFTX results demonstrate reasonable agreement with the dye tracer study given the complex porous nature of the UFA. For Wekiwa Spring, the ECFTX model estimates a faster travel time, suggesting matrix flow in the UFA at portions of the dye flow path. For Rock Spring, the 7-day dye tracer finding is faster than that predicted by ECFTX and indicates that the Rock Spring dye may have traveled via UFA conduit flow.

5.2. EVS Model

EVS is a modular geostatistical software that combines advanced volumetric gridding with four-dimensional visualization (i.e., three dimensions in space and time). The software allows for the integration of disparate datasets into a comprehensive analysis framework. For this project, EVS was leveraged to integrate results from the ECFTX model with lithologic constraints derived from wells within the project study area.

5.2.1. EVS Subsurface Lithology

Lithologic information from 139 FGS wells were utilized to constrain the subsurface geology around the Wekiwa project area. For these FGS wells, lithologic information and formation picks were downloaded from the FDEP GIS data portal[17]. Downloaded formation picks were identified by FGS geologists. Most of the formation picks followed a standardized nomenclature that is listed below.

[17] https://www.arcgis.com/home/item.html?id=0f5739c0409e4e9db5c63ab8df6d9e34

- ZTCU – Undifferentiated Sediments
- HTRN – Hawthorne Group
- OCAL – Ocala Limestone
- AVPK – Avon Park Formation

Some of the downloaded wells utilized FGS formation picks that differed from the above nomenclature. These differences were generally minor and included novel formation picks such as lithologic differentiation within the uppermost sediments or detailed subunit picks within the Hawthorne Group. For wells with these non-standard formation picks, Drummond Carpenter geologists utilized the well's lithologic information to reassign the formation picks using the more-standardized nomenclature listed above.

In addition to the FGS wells, Drummond Carpenter geologists made formation picks on another 38 wells drilled in the Wekiwa project area (Figure 19). Formation picks were completed using the lithologic information available from the wells. In general, the formation picks from these wells showed excellent agreement with the surrounding FGS wells.

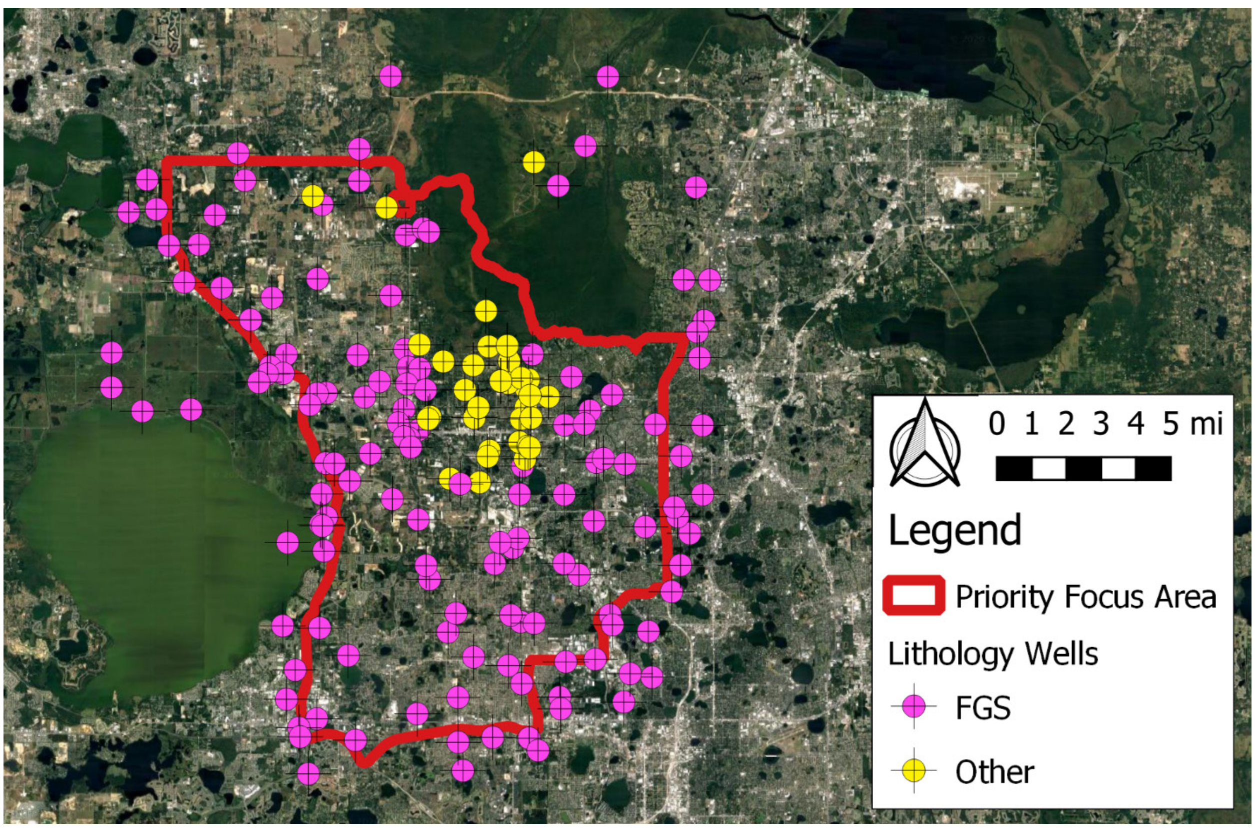

Figure 19. Distribution of lithology wells used to develop the geologic model.

Within EVS software, a 3-dimensional model of the geologic formations was developed by first creating a triangulated irregular network that linked formation identifications from the individual wells. The triangulated irregular network was then discretized within a convex hull surrounding the wells using the Nearest Neighbors algorithm. This helped produce a detailed geologic model which approximates the subsurface geologic conditions throughout the Wekiwa project area.

5.2.2. EVS Visualization

EVS software was utilized to visualize results from ECFTX simulations alongside the subsurface geology. The resulting EVS visualization utilizes the NAD83/Florida East (ft US) coordinate system. The geological model described above was loaded into EVS and visualized along two cross sections. The cross sections are straight, rotatable, and translatable across the geologic model. Particle pathways from the ECFTX simulations were loaded into EVS as animated lines. The particle pathways are colored by velocity (ft/day). Particles may be animated and move as conical glyphs along the pathways at times corresponding the output from the ECFTX simulation. Additionally, to aid with the EVS visualization a digital-elevation-model was downloaded from the USGS The National Map[18] and aerial imagery was downloaded from Google Earth[19] (Figure 20).

The combined visualization of the ECFTX simulations and the subsurface geologic layering can provide insight into how groundwater moves throughout the Wekiwa project area (Figure 21). Within the Unconsolidated Sediments and Hawthorne Group, groundwater primarily moves in a vertical fashion at velocities less than 20 ft/day. Once the groundwater reaches the Ocala Limestone and Avon Park Formation it is within the UFA. Within the UFA groundwater movement is much more lateral and reaches velocities between 20-50 ft/day. Near springs like Wekiwa Spring, groundwater velocities may be much higher and reach velocities between 50 and 100 ft/day.

[18] https://viewer.nationalmap.gov/basic/#startUp

[19] https://www.google.com/earth/

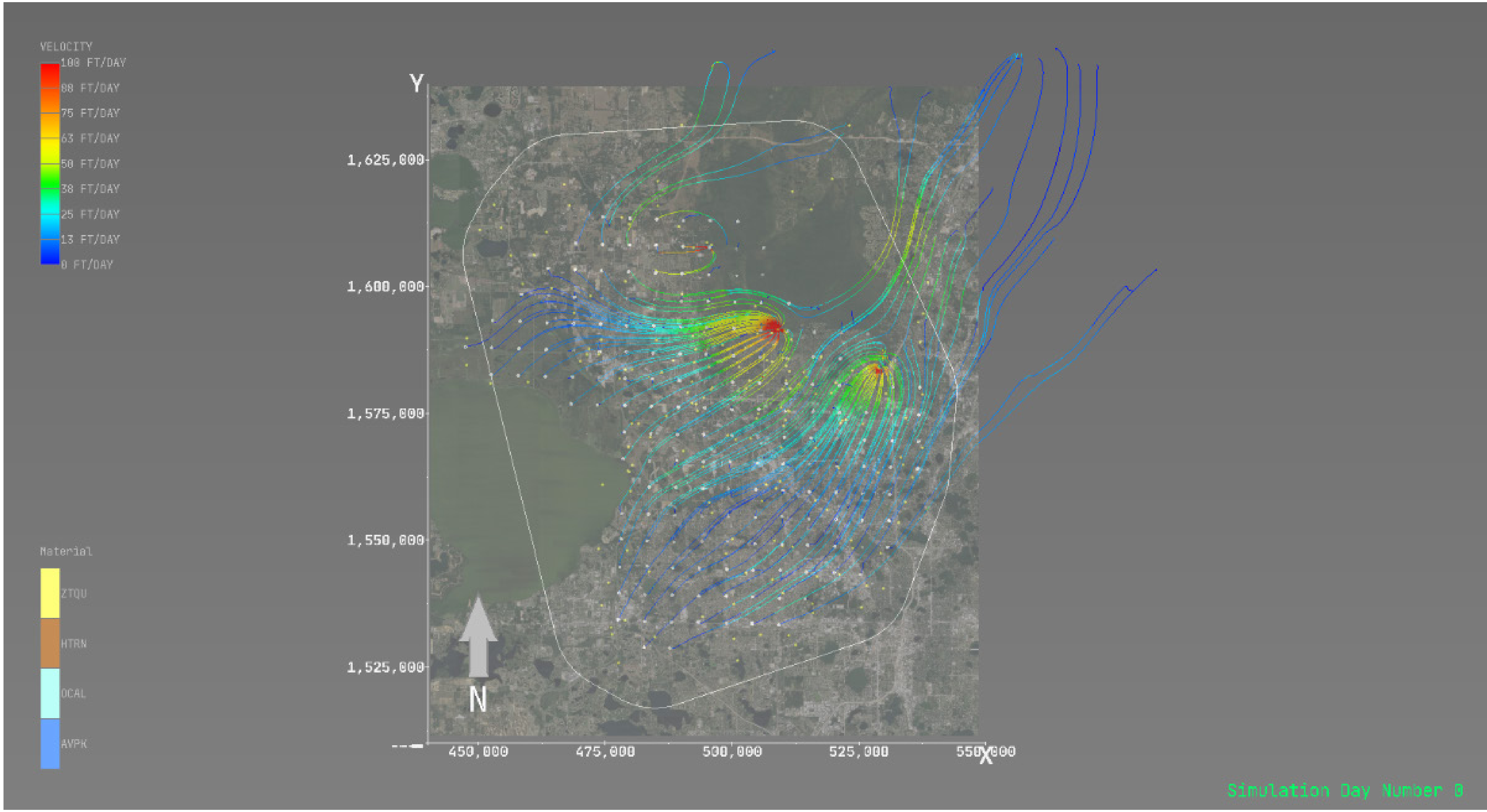

Figure 20. Overhead view of the EVS model showing ECFTX particle pathways and velocities.

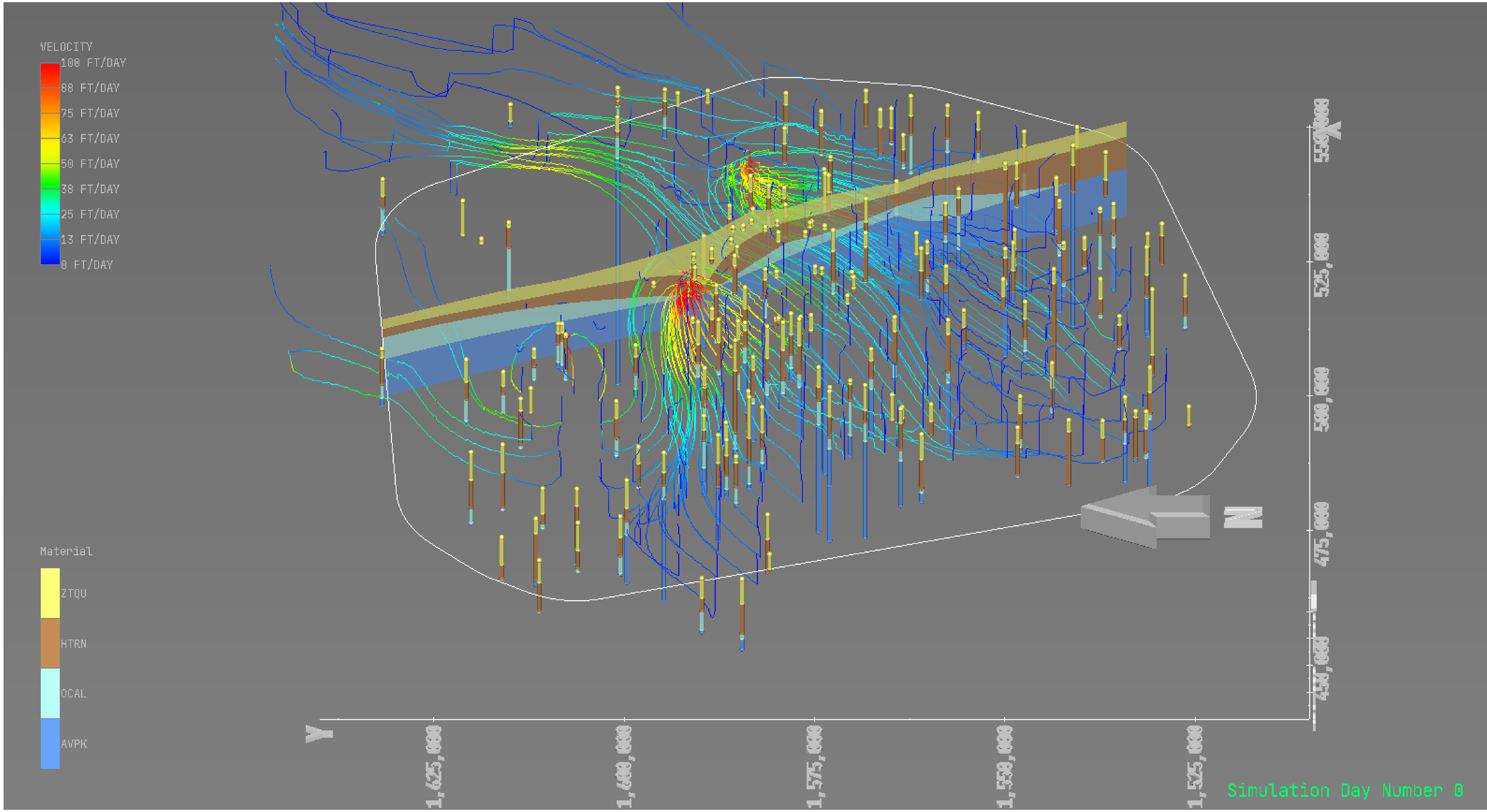

Figure 21. Oblique view of the EVS model showing the intersection of the 3-dimensional particle pathways with a geologic cross section across Wekiwa Spring.

The EVS visualization was output as an EVS Presentation (.evsp) model. This model allows users to interact with the visualization in demonstration mode without requiring an EVS license. A copy of the Wekiwa EVSP model is included in the project electronic deliverables.

5.3. ECFTX and EVS Model Conclusions

ECFTX represents a suitable regional groundwater model to assess groundwater flow and dissolved nitrate transport within the Wekiwa BMAP. It is noted that ECFTX is not a water quality model and these results do not consider complex biogeochemical changes that would alter dissolved nitrate concentrations throughout the groundwater system. The following conclusions and potential implications can be drawn related to future nitrate mitigation strategies:

(1) Areal portions of the groundwater basin within the Wekiwa BMAP may not regularly contribute groundwater, and thus nitrate pollutant load, to Wekiwa Spring or associated Wekiwa BMAP waterbodies. Therefore, nitrate mitigation efforts in these areas may not provide optimal benefit to the water quality of Wekiwa Spring. Additional field studies, such as dye tracer tests, could be performed to validate these findings during typical hydrologic years.

(2) The groundwater travel time within the PFA to Wekiwa Spring varies greatly, with those areas immediately south and southwest of Wekiwa Spring having the fastest travel time to the spring. This helps validate previous findings that the water from Wekiwa Spring is young, relative to the age elsewhere within the springshed, which is likely due to the high recharge areas in the vicinity of the spring.

(3) Given that denitrification in the Wekiwa springshed increases with increased groundwater travel time, those “young” areas with limited groundwater travel can be expected to have reduced denitrification and thus have a greater potential impact on nitrate loading to Wekiwa Spring. This finding can help prioritize nitrate mitigation efforts, such as septic to sewer replacement sites.

(4) Lateral travel distances within the SAS and IAS are generally less than 2,000 feet (as measured from the water table), and less than 1,000 feet in the fast groundwater travel areas. This suggests that nitrate samples collected in SAS and IAS wells generally originate from a relatively localized area. This finding can help attribute nitrate loading with nearby land uses within given distances from wells.

(5) The refined ECFTX model was run using a steady-state simulation calibrated to the 2003 period. Steady-state modeling provides a ‘snapshot in time’ simulation that does not consider fluctuations in rainfall, evapotranspiration, recharge, and other inputs over time. To assess seasonality, the ECFTX model could be modeled under transient conditions over multiple years which would show changes in groundwater flux, velocity, and transport at different times. Additionally, chemical constituent fate and transport modeling could be performed to provide detailed predictions of concentrations in groundwater both spatially and temporally.

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6. GAP SUMMARY & OVERALL RECOMMENDATIONS

Table 6 provides a summary of identified gaps in the current nitrate sourcing study. SIAR modeling completed by Drummond Carpenter, discussed in Section 4.2, addresses some of the listed gaps. Additional recommendations related to the gap analysis are provided in Section 7.

Table 6. Gap Analysis Summary

Gap & Recommendation	Justification
Gap: Limited temporal nitrate and nitrate isotope data. **Recommendation**: Collect higher frequency data.	As more data are collected, seasonal trends in nitrate concentrations may become more apparent. Additionally, larger sample sizes and higher temporal resolution of isotopic data will improve characterization of each location, possibly better capture fertilizer application periods, and strengthen the current isotopic mixing model results.
Gap: Limited spatial nitrate and nitrate isotope data. **Recommendation**: Install additional well clusters.	Expanding the well network will improve nitrate sourcing. Proposed locations were chosen based on nitrate 'hotspots', high recharge areas, fast travel times to Wekiwa Spring, data gaps, sanitary sewer service areas, and right-of-way availability.
Gap: Uncertainty in isotope mixing model. **Recommendation**: Develop localized source distributions for SIAR (i.e., end member sampling of suspected nitrate sources). **Recommendation:** Adjust SIAR model using informative prior distributions.	In the SIAR model, assigned source distributions are relied on to estimate relative contributions of individual nitrate sources to the waterbody of interest; therefore, the performance of the model depends on the assumption that the source isotopic signatures are representative. End member sampling can be used to create localized source distributions. Prior distributions of expected sources (e.g., incorporating land use and septic density to form priors) can be used to help guide the SIAR modeling of source proportions.
Gap: Uncertainty in isotope mixing model. **Recommendation**: Remove the soil end member in SIAR.	The soil end member confounds the SIAR model due to overlapping source distributions. Since soil nitrate is expected to contribute low concentrations (0.02 mg/L nitrate-N), it should be removed from the model as an insignificant source.
Gap: Uncertainty in isotope mixing model. **Recommendation**: Account for denitrification in SIAR.	The denitrification end member allows the SIAR model to assign some portion of enriched samples to denitrification that may have been inappropriately assigned to sewage/manure without consideration of denitrification.
Gap: Limited understanding of groundwater transport in the SAS, IAS, and UFA aquifers. **Recommendation**: Perform additional dye tracer studies to track travel time and fate of groundwater flow.	There is a limited understanding of groundwater transport within the Wekiwa BMAP area. The refined ECFTX (steady-state) groundwater model suggests that the Wekiwa springshed covers a limited portion of the overall BMAP area, making it important to understand where nitrate control practices are warranted if spring vent nitrate reduction is a goal.

Gap & Recommendation	Justification
Recommendation: Perform regional transient groundwater modeling to assess springshed flow over multiple years.	A calibrated transient version of the refined ECFTX model would provide greater detail as to the response that rainfall has on groundwater travel and velocity across wet and dry periods and can be used to improve the County's fertilizer ordinance. Additionally, chemical constituent fate and transport modeling could be performed to provide detailed predictions of concentrations in groundwater both spatially and temporally.

7. DETAILED RECOMMENDATIONS

Considering the County's goal to assess the impact of fertilizer on nitrate loading within the Wekiwa springshed, four primary recommendations for future work to support the County's current nitrate sourcing study have been identified by the gap analysis and include the following:

(1) increase frequency of data collection at existing wells,

(2) install additional well clusters,

(3) make updates to the SIAR model, including the following:

a) develop localized source distributions

b) remove the soil end member, and

c) add denitrification end member to improve the SIAR modeling

(4) Develop a calibrated transient groundwater model of the springshed to assess seasonal groundwater transport, travel times, velocity, and flux to develop a more optimal nitrate fertilizer restriction period in the County's fertilizer ordinance.

Each recommendation is described in detail in the following sections.

7.1. Increase Frequency of Data Collection at Existing Wells

The first recommendation is to collect more frequent isotopic data for existing sampling locations. As discussed in Section 4.2, larger sample sizes and higher temporal resolution of isotopic data will improve the characterization of each location, possibly better capture fertilizer application periods, and strengthen the current isotopic mixing model results.

Based on preliminary results from the ECFTX model, a subset of wells reaches the spring faster or more consistently. A recommended approach is to increase sample frequency from quarterly to monthly, which will provide a dataset with a greater potential to reduce uncertainty in nitrate sources and increase an understanding of any seasonality trends. Eleven locations, including the spring vent, are ranked in priority for monthly data collection (Table 7).

Table 7. Priority ranking of wells selected for monthly sampling.

Priority Rank	Well / Station	Justification
1	MW04/R	Highest average nitrate concentrations
2	MW07	Potential observed relationship between precipitation and nitrate concentrations
3	MWBU	Currently sole UFA well with isotopic data
4	MWBS	Opportunity to further explore nitrate travel from SAS to UFA (MWBU)

5	SW01	Provides insight to mixing of SAS, IAS, UFA water at spring
6	MW11	Robust existing dataset
7	MW22[20]	Current data suggests high NH_4^+/Urea fertilizer contribution
8	XDEPPBS	Limited data, ECFTX suggests relatively fast travel time to spring
9	MW17	Limited data, ECFTX suggests relatively fast travel time to spring
10	MW02	Limited data, ECFTX suggests relatively fast travel time to spring
11	MW01	Isotope analysis could reveal the source of elevated ammonia

7.2. Additional Well Clusters

Dissolved nitrate is assumed to come from a mixture of various sources within the Wekiwa springshed, including fertilizer, human and animal waste, reclaimed wastewater, and natural sources (soil, atmospheric). Several previous studies performed within the Wekiwa springshed have identified fertilizer as the dominant nitrate source, which has in part led to the County's efforts to install the existing well clusters. These existing well clusters have been strategically placed to detect fertilizer nitrate while limiting, to the extent practical, other potential nitrate sources that would make identification of fertilizer nitrate difficult.

The following recommendations for additional well clusters are provided to expand the County's current groundwater quality monitoring network to further their existing evaluation of fertilizer nitrate and to strategically assess other potential nitrate sources. The following criteria were considered subject to their associated relevance to nitrate sources and this study.

(1) **Location of existing wells** – As shown in Exhibit 13, the location of existing wells within the Wekiwa PFA is generally limited to the immediate south and southwest of the spring. Other areas primarily to the west of the spring do not have active monitoring. The County may benefit from a more spatially representative monitoring network. Additionally, water quality data should be collected in areas that are expected to flow to Wekiwa Spring if a direct comparison of water quality data is to be performed. Per Exhibit 13, some wells located to the

[20] Per Map 1, MW22 is shown to be outside of the Wekiwa Spring UFA capture area, based on the results of the ECFTX model. However, the ECFTX model represents a snapshot in time, and groundwater around MW22 may discharge to Wekiwa Spring under certain scenarios. For this reason, as well as the large number of existing isotope samples already collected, this well is recommended to be sampled at an increased frequency.

south of Wekiwa Spring may bypass the spring under specific groundwater flow conditions based on the presented ECFTX steady-state model results.

(2) **Aquifer units** – Collecting representative water quality data from the aquifer units is also important to understand the fate and transport of nitrate within the groundwater system. Refer to Exhibit 3 for a depiction of aquifer unit sampling by well.

(3) **Measured nitrate loads** – Certain areas within Wekiwa are consistent nitrate "hotspots" and additional monitoring and sampling should prioritize these areas to better define potential high nitrate load sources. Refer to Exhibit 5.

(4) **Land use** – The existing wells are generally sampled in and around residential areas and golf courses, where the highest amounts of fertilizer are expected to be applied. Land use evaluation within Wekiwa springshed is being evaluated by a separate County consultant to consolidate areas of expected high nitrate application. It is recommended that this information be provided to Drummond Carpenter when available to aid in future well cluster assessments.

(5) **Septic tank locations** – Septic systems are considered a source of nitrate loading to Wekiwa Spring. Previously, the sampling wells were generally excluded in known septic areas to avoid masking the fertilizer nitrate signature. However, current County efforts to disconnect septic systems and replace with centralized sewer presents an opportunity for the County to assess the change in nitrate and isotope signature before and after communities are retrofitted with sewer.

(6) **Reclaimed wastewater application** – Areas irrigated with reclaimed water provide an additional potential source of nitrate to Wekiwa Spring. Currently, the County's monitoring well network does not include sampling of wells within areas being irrigated by reclaimed wastewater.

(7) **Relative age and travel path of groundwater** – Existing studies within the Wekiwa springshed have demonstrated that over 70% of the nitrate in the UFA may be removed from the groundwater via denitrification, and that additional denitrification is also likely occurring in the intermediate and surficial aquifer layers. Studies have found that groundwater traveling through the aquifer system at a faster rate can expect lower amounts of denitrification to occur than groundwater moving more slowly through the aquifer (Byrne et al. 2012). Therefore, areas of relatively short travel were prioritized for additional well clusters, as these areas may have a greater impact on nitrate transport. The travel time of groundwater was derived from particle tracking based on the ECFTX model.

Wastewater treatment facilities were not considered in the proposed well cluster recommendations.

Six priority locations for additional well clusters have been identified based on land use, available data, and preliminary ECFTX model results (Exhibit 17).

Priority Location 1: Sweetwater Golf and Country Club Transects

The Sweetwater Golf Course represents areas within the Wekiwa PFA with the highest observed concentrations of nitrate. The MW04/R well location has consistently had the highest concentration of nitrate in wells monitored by the County, and the nitrate sampling performed by Geosyntec (2021) similarly showed elevated nitrate levels in sampled groundwater. This golf course and country club, located immediately south of the spring vent, has a predicted very fast travel time to the spring with minimal opportunity for denitrification to occur. Based on a review of the available County nitrate and isotope data, this area represents the highest potential source of nitrate in the vicinity of the spring vent.

To establish the groundwater nitrate loads and likely sources associated with the country club or surrounding properties, a deployment of well clusters within the county right-of-way is proposed. Three transects of three well clusters (collocated SAS or IAS and UFA wells) are proposed to be installed along Wekiwa Spring Road, Sweet Water Country Club Drive, and along the pond located north of Duquesne Avenue for a total of 18 wells to form north-south transects. These wells will allow for observation of nitrate (and other water quality parameters) in groundwater before reaching, passing through, and leaving the golf course. The proposed location of priority 1 well clusters are shown on Exhibit 18.

Priority Location 2: Planned Septic Tank Retrofit Project Area

There is a planned retrofit project for subdivisions within the Wekiwa PFA (Y20-815 OCU Wekiwa Spring Septic Tank Retrofit Project) that will remove approximately two hundred septic systems and replace service with centralized sewer. None of the current sampling locations fall within the planned project area. Placing a well cluster within this area could provide insight on the impact of septic retrofits on nitrate loading.

A well cluster of two wells is recommended with one screened in the SAS, if present, and the second screened in the IAS. If the SAS is not present, two wells screened in the IAS and UFA are recommended. The proposed location of priority 2 well cluster is shown on Exhibit 18.

Note that based on the upcoming construction project within the neighborhood, direct push technology (DPT) sampling may be preferred if the construction impacts proposed monitoring well locations.

Priority Location 3: MW07 Cluster

MW07 is screened in the SAS and has the most consistent isotopic data set with a total of 13 isotopic data measurements, average nitrate-N concentration of 2 mg/L, and observed correlations between nitrate concentration and precipitation. Adding a well at MW07 would help to evaluate seasonality patterns.

A well screened in the IAS is recommended to be collocated with MW07. The proposed location of the IAS well adjacent to MW07 is shown in Exhibit 19.

Priority Location 4: Errol Estates Country Club

Preliminary particle tracking results show the area to the west-southwest of MW01, near Errol Estates Country Club, has relatively fast travel times to the spring and a properly placed well cluster has the potential to uncover the impact of applying reuse water to the golf course on nitrate loading.

A well cluster screened in the SAS and IAS is recommended for this location. Exhibit 20 shows the potential location for the SAS and IAS wells near the country club.

Priority Location 5: MW01 Cluster

Based on the particle tracking results, a significant land area west of Wekiwa Spring is not being sampled in the Upper Floridan Aquifer. This would include much of the area associated with central and northern Apopka, Zellwood, and other unincorporated areas near the north shore of Lake Apopka. The UFA wells currently sampled collect groundwater in flow areas associated with South Apopka as well as unincorporated areas immediately south of Wekiwa Spring. Installing an UFA well near MW01 could provide insight as to nitrate levels in this portion of the springshed. If nitrate levels are elevated enough, then isotope data could also be collected and analyzed. Per the ECFTX particle tracking simulations, the groundwater recharging from Errol Estates Country Club flows toward the MW01 well, potentially yielding UFA groundwater that originated from this location.

Additionally, it is recommended that an IAS well be installed near MW01 to assess changes in ammonia, which is elevated in the existing SAS well. Because vertical recharge is expected in this area, assessing the extent of nitrification of ammonia through the SAS could provide better understanding regarding how nitrogen fractionation occurs in different parts of the watershed. MW01 is in a sewer area, and the cause of elevated ammonia is unclear. Isotope testing of MW01 wells could help determine the origin of the elevated ammonia. Exhibit 20 shows the potential location for the MW01 cluster.

Priority Location 6: Zellwood

Preliminary particle tracking results revealed the area near Zellwood also has relatively short travel times to the spring. Based on preliminary land use analysis, the area is relatively undeveloped compared to locations of other study wells. A well in this area could potentially serve as a background well in the study if no major anthropogenic nitrate source is discovered in the area.

A well screened in the SAS is recommended for this proposed location. The proposed location of the SAS well in Zellwood is shown in Exhibit 21.

7.2.1. Ranking of Additional Well Clusters

The six proposed additional well clusters are listed based on priority in Table 8.

Table 8. Priority ranking of additional well clusters to install.

Priority Rank	Well Cluster	Proposed Well ID	Sample Collection Frequency	Justification
1	Proposed Location 1: Golf Course Transects	PWC-1A-1I	Monthly	MW04/R-highest average nitrate concentrations
2	Proposed Location 2: Planned Septic Tank Retrofit Project Area	PWC-2A, PWC-2B	Monthly	May provide insight on the impact of the retrofit on nitrate loading
3	Proposed Location 3: MW07 Cluster	PWC-3	Monthly	Robust existing dataset

4	Proposed Location 4: Country Club	PWC-4A, PWC-4B	Monthly	Fast travel times to the spring
5	Proposed Location 5: MW01 Cluster	PWC-5A, PWC-5B	Quarterly	Spatial gap in dataset
6	Proposed Location 6: Zellwood	PWC-6	Quarterly	Potential for a background well

7.3. SIAR Model Update Recommendations

Several recommendations are proposed to update the Wekiwa SIAR model used to estimate nitrate sources. The first recommendation is to develop localized source distributions. The goal of this recommendation is to improve confidence in the SIAR model source allocations. As discussed in Sections 2.2 and 4.4, source distributions are used by the SIAR model to identify nitrate source signatures in the isotopic data of each well.

End member sampling of nitrate sources is suggested to help refine source distributions for use in the SIAR model. The measured isotopic signatures of end members can be used in conjunction with literature values to develop mean and standard deviations for each nitrate source to be used in the model.

To reduce uncertainty in the isotopic mixing model, removing the soil end member is recommended. The soil end member significantly overlaps with the NH_4^+/Urea fertilizer and sewage/manure end members. Thus, including the soil end member in the model confounds the model and increases uncertainty. Removing the soil end member from the model is anticipated to have negligible negative impact on unallocated soil nitrate proportions, since soil nitrate is expected to contribute low concentrations (approximately 0.02 mg/L nitrate) relative to total nitrate observed in study wells.

Since denitrification is suspected in many of the study wells, accounting for its impact is important for the SIAR model to accurately assign nitrate sources. Creating a denitrification end member in SIAR is an effective way to improve source apportionment by adding consideration of source signature alteration through isotopic enrichment caused by denitrification.

Finally, the SIAR modeling can be improved by incorporating informed prior distribution into the Bayesian framework. Such information could include adjusting prior parameters of septic and manure sources for wells located in areas of dense septic coverage and agricultural land use, or fertilizer parameters in residential areas where more intense fertilizer hot spots are likely (refer to Section 2.4.3).

7.4. Develop Calibrated ECFTX Transient Model

The refined steady-state ECFTX model developed by Drummond Carpenter, discussed in Section 5, illustrates the importance of understanding groundwater transport within the springshed. Portions of the Wekiwa BMAP are modeled as not contributing to groundwater flow at the Wekiwa Spring vent. Some of the groundwater within the BMAP flows to other springs, which discharges to the Wekiva

River, an impaired waterbody also regulated under a BMAP. However, some areas are modeled (under steady-state conditions) to bypass the BMAP surface waters altogether.

This is an important finding for the County to consider when implementing various nitrate intervention efforts, such as structural or nonstructural best management practices. Measuring the nitrate concentration response of such intervention effort depends on the travel time and destination of the groundwater, which varies spatially across the entire BMAP.

The development of a calibrated transient model of ECFTX, within the BMAP limits, can increase the understanding of groundwater behavior of the Wekiwa system and the impact of seasonality factors. Most notably, a transient model can demonstrate how precipitation and recharge impacts groundwater travel time and transport throughout the year, which is something steady-state analyses cannot achieve. This may be beneficial for the County, should changes to allowable nitrate fertilizer applications periods be warranted to structure more targeted and effective fertilizer ordinance restriction periods.

8. CONCLUSIONS

The primary goal of this project is to evaluate whether groundwater nitrate within the Wekiwa springshed can be attributed to nitrate sources, particularly the seasonal application of fertilizer, and how this information can inform future Wekiwa nitrate reduction strategies. Nitrate loading in the Wekiwa springshed is influenced by several factors including precipitation, geology, and land use. The following represents a summary of the work performed by Drummond Carpenter and the project conclusions:

1) Review of Wekiwa literature suggests fertilizers, septic systems, and wastewater treatment facilities are likely notable contributors to nitrate within the springshed with fertilizer most commonly referenced as the dominant source.
2) The gap analysis revealed opportunities for additional data collection, isotope mixing model refinement, spatial land use analysis, and further exploration of seasonality.
3) The County's fertilizer ordinance restricts nitrate fertilizer application during the wet season from June to September.
    - Currently, strong seasonal trends have not been observed in the existing data. There are several factors that may preclude observation of seasonal trends in nitrate including dataset size, variable fertilizer application frequencies and locations, use of irrigation in residential and golf course areas, fluctuating denitrification rates, inconsistent travel paths from nitrate sources, and varying aquifer units (sampling depth).
    - The fertilizer ordinance was adopted in 2017, consistent with the beginning of the nitrate and nitrate isotope monitoring work performed by the County and used in this study. Nitrate isotope data in the Wekiwa springshed is generally limited or unavailable in earlier years.
    - The notion that a summer fertilizer ban has the potential to reduce nitrogen leaching to the groundwater is supported by findings from the 2021 nitrogen transport modeling study conducted for the Wekiwa BMAP area (Drummond Carpenter 2021):
        - Fertilizer nitrogen applied before high precipitation events is susceptible to greater leaching, particularly fertilizer containing lower amounts of slow-release nitrogen, compared to fertilizer nitrogen application during a period without a high precipitation event.
        - The mass of fertilizer nitrogen predicted to leach to groundwater increased with increases to the modeled fertilizer application rate.
4) Denitrification is the process whereby nitrate is reduced to nitrogen gas by denitrifying bacteria and can dramatically reduce dissolved nitrate in groundwater systems such as Wekiwa.
    - The data provide strong evidence that denitrification is occurring within multiple aquifer units based on linear isotopic enrichment of samples (covariation of $\delta^{15}N$: $\delta^{18}O$) correlated with decreasing dissolved oxygen values. Denitrification within the springshed likely has a profound impact on nitrate concentrations at the Wekiwa spring vent.

5) Groundwater travel times may be a controlling factor for nitrate concentrations at Wekiwa Spring with faster travel times leaving less time for denitrification to occur causing higher nitrate concentrations.
    - Therefore, areas of high nitrogen load to the land surface, with high recharge potential and fast travel times to the spring may represent the highest priority locations for additional County monitoring, intervention, or retrofitting.
    - While areas closer to Wekiwa Spring were generally modeled to have faster groundwater travel times than areas farther away, some areas nearby the spring were modeled as having relatively long travel times. It is therefore not recommended to assume that proximity to the spring will always yield faster travel times, lower denitrification potential, and therefore higher nitrate loading.
6) The SIAR model developed by Wood (2020) has been modified by Drummond Carpenter to reduce uncertainty by adjusting end member sources (e.g., fertilizer, atmospheric, soil, manure) based on literature-supported modeling assumptions of similar karst groundwater systems. The updated SIAR model provided the following results:
    - The updated SIAR model estimated that fertilizers were the top contributors to total nitrate in 10 of the 12 wells/stations included in modeling performed by Drummond Carpenter.
    - The updated SIAR model estimated that approximately 80% of the nitrate in well MW04/R is attributed to fertilizer. MW04/R well is located in Sweetwater Golf and Country Club, which represents the area of highest known groundwater nitrate concentrations in this study. Recent groundwater monitoring completed by Geosyntec Consultants within this country club found additional hotspots of nitrate, providing further evidence of high-nitrate sources in this area immediately south of Wekiwa Spring.
7) While the findings of this study demonstrate fertilizers are a leading nitrate source in Wekiwa PFA, this study does not negate the importance or influence of other identified nitrate sources, such as septic systems. This was a targeted study to understand the impact of fertilizer application and seasonality within the Wekiwa PFA with a strategic well network installed generally near residences on sanitary sewer and not septic. Installing new well clusters in septic areas may increase the number of locations where septic systems are a dominant source.
8) A transient groundwater model of the Wekiwa BMAP would help understand the seasonal groundwater travel times and pathways to Wekiwa Spring, which may help structure a more effective fertilizer ordinance that reduces the usage of nitrate fertilizer to more targeted, data driven time periods.

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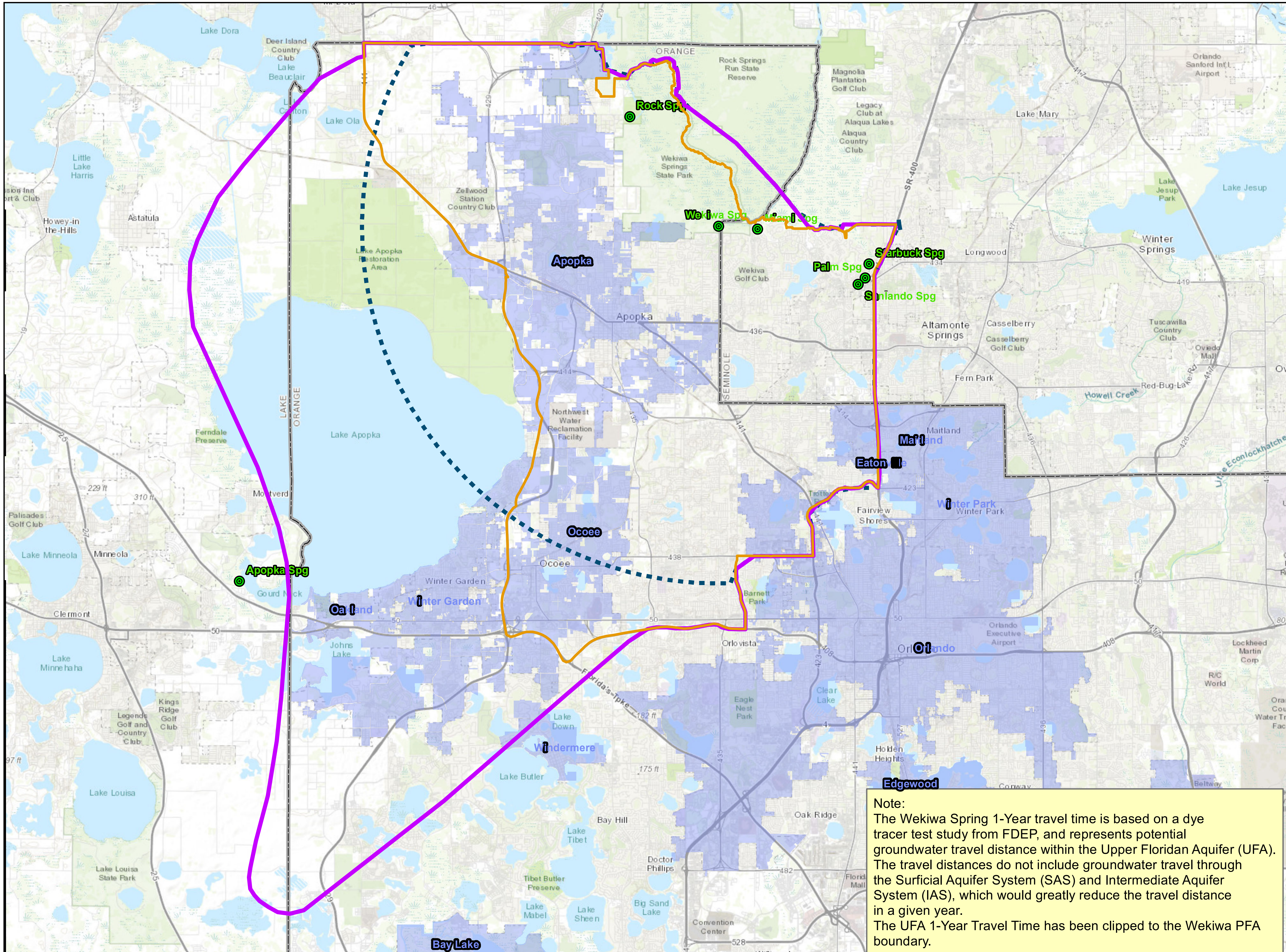
EXHIBITS



Note:
The Wekiwa Spring 1-Year travel time is based on a dye tracer test study from FDEP, and represents potential groundwater travel distance within the Upper Floridan Aquifer (UFA). The travel distances do not include groundwater travel through the Surficial Aquifer System (SAS) and Intermediate Aquifer System (IAS), which would greatly reduce the travel distance in a given year.
The UFA 1-Year Travel Time has been clipped to the Wekiwa PFA boundary.

ORANGE COUNTY GOVERNMENT FLORIDA

DRUMMOND CARPENTER engineering + research

N

0 2 4 Miles

LEGEND

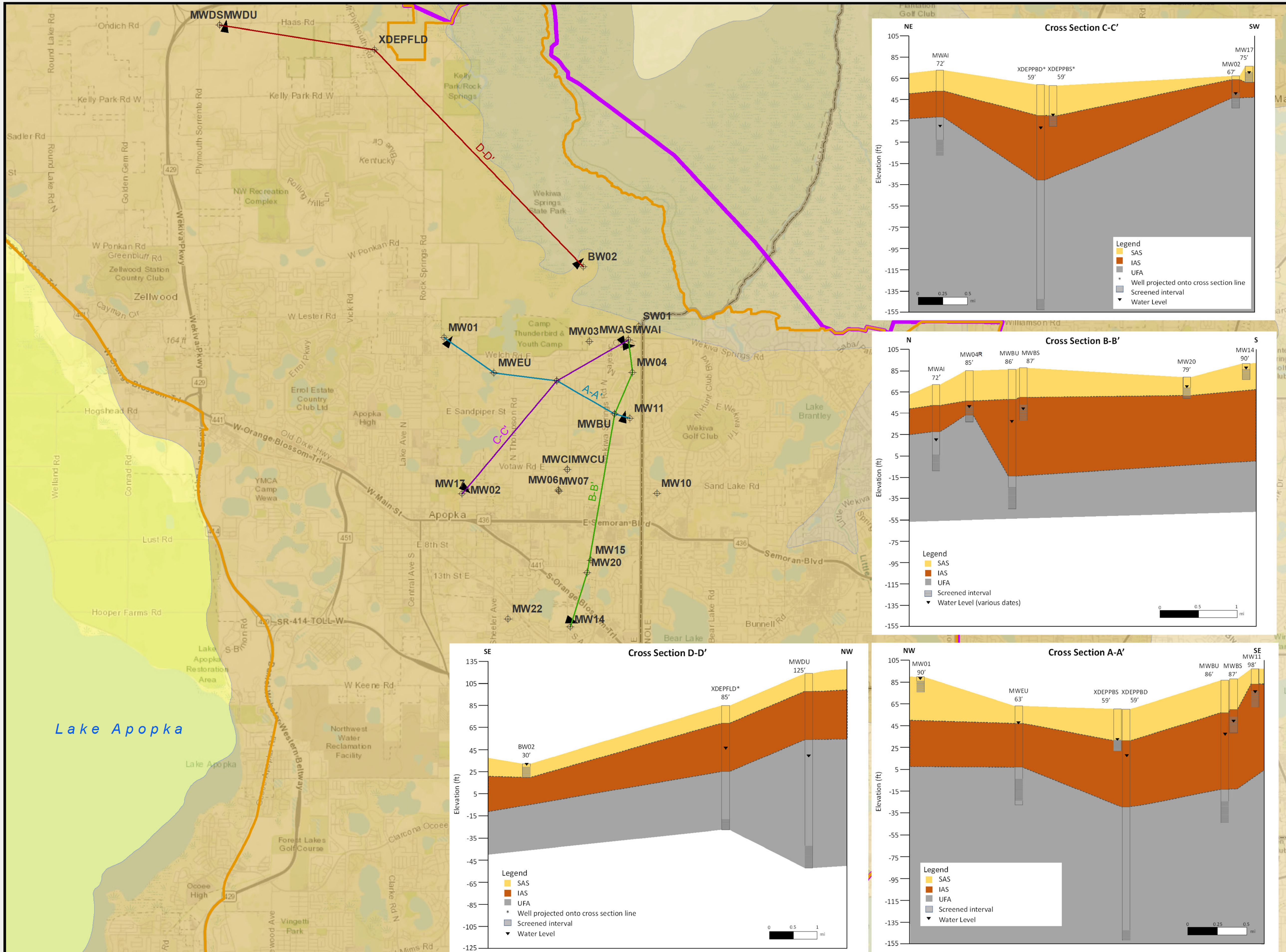
- Springs
- Wekiwa UFA 1-Year Travel
- Wekiwa Priority Focus Area
- Wekiwa BMAP
- Orange County
- Cities

Sources:
Background: ESRI
Roads: Orange County Boundary, 2017
Wekiwa BMAP: FDEP, 2018
Wekiwa PFA: FDEP, 2019
GW Travel Time: FDEP, 2015

Exhibit
1

Wekiwa Springs BMAP and PFA Extents

Wekiwa BMAP Gap Analysis



ORANGE COUNTY GOVERNMENT FLORIDA

DRUMMOND CARPENTER engineering + research

N

0 1 2 Miles

LEGEND

- Wekiwa Monitoring Wells
- Wekiwa BMAP
- Wekiwa Priority Focus Area
- Orange County

Cross Sections

- A-A'
- B-B'
- C-C'
- D-D'

Formation

- Cypresshead Fm
- Hawthorn Group
- Holocene Sed
- Undifferentiated Sed

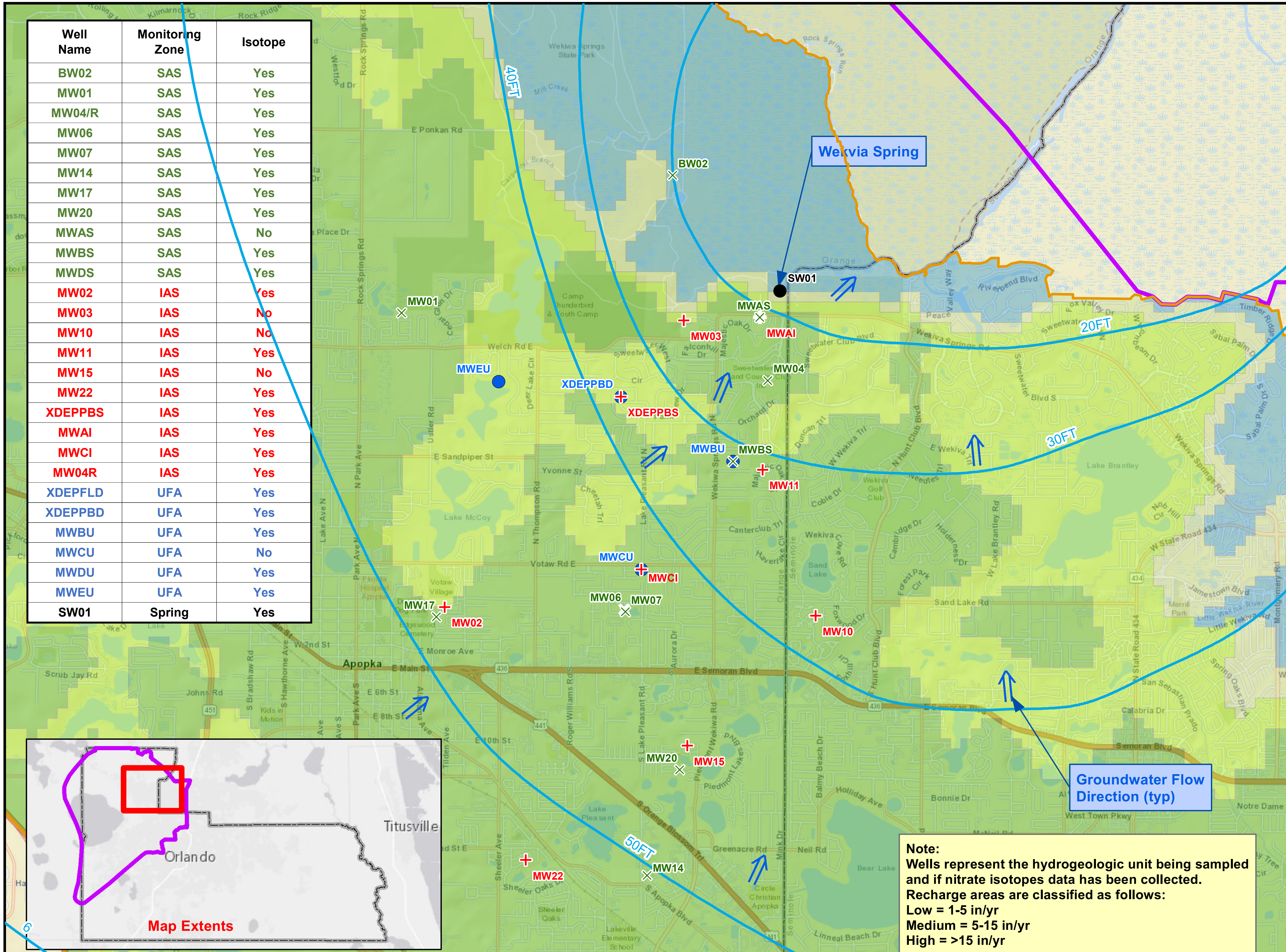
Sources:
Background: ESRI
Wells: Orange County, 2020
Wekiwa BMAP: FDEP, 2018
Wekiwa PFA: FDEP, 2019

Exhibit

2

Wekiwa Geology and Monitoring Well Lithology

Wekiwa BMAP Gap Analysis



Well Name	Monitoring Zone	Isotope
BW02	SAS	Yes
MW01	SAS	Yes
MW04/R	SAS	Yes
MW06	SAS	Yes
MW07	SAS	Yes
MW14	SAS	Yes
MW17	SAS	Yes
MW20	SAS	Yes
MWAS	SAS	No
MWBS	SAS	Yes
MWDS	SAS	Yes
MW02	IAS	Yes
MW03	IAS	No
MW10	IAS	No
MW11	IAS	Yes
MW15	IAS	No
MW22	IAS	Yes
XDEPPBS	IAS	Yes
MWAI	IAS	Yes
MWCI	IAS	Yes
MW04R	IAS	Yes
XDEPFLD	UFA	Yes
XDEPPBD	UFA	Yes
MWBU	UFA	Yes
MWCU	UFA	No
MWDU	UFA	Yes
MWEU	UFA	Yes
SW01	Spring	Yes

Note:
Wells represent the hydrogeologic unit being sampled and if nitrate isotopes data has been collected.
Recharge areas are classified as follows:
Low = 1-5 in/yr
Medium = 5-15 in/yr
High = >15 in/yr

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N

0 0.5 1 Miles

LEGEND

Wells

Monitoring Zone
- SAS
- IAS
- UFA
- Spring

- POT Contour
- Wekiwa PFA
- Wekiwa BMAP
- County

Recharge
- Discharge
- Low
- Medium
- High

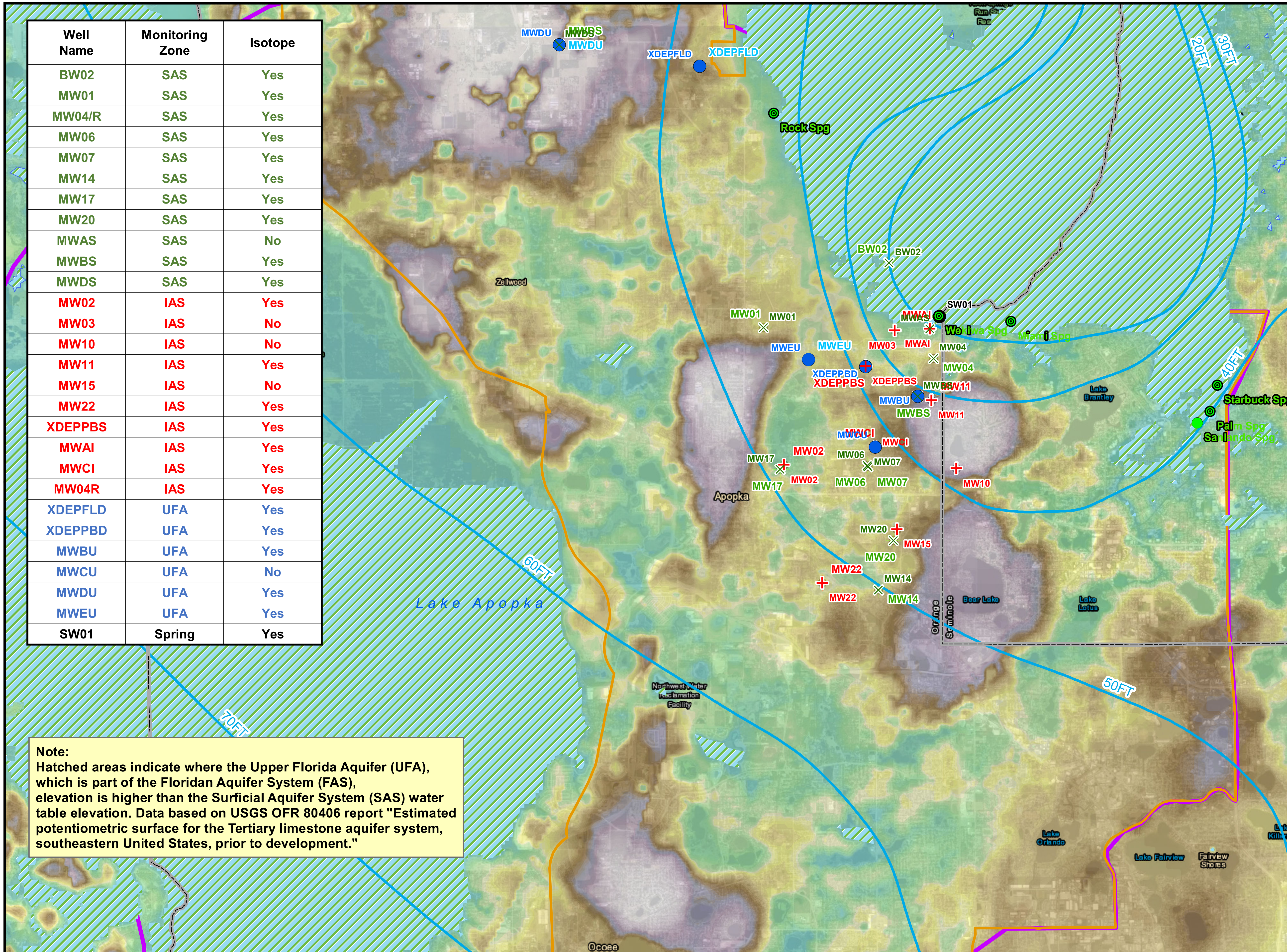
Sources:
Background: ESRI
Recharge: SJRWMD, 2016
Potentiometric Surface: FGS, 2017 (NAVD88)
Wells: Orange County, 2020

Exhibit
3

Wekiwa Recharge and Monitoring Locations

Wekiwa BMAP Gap Analysis

Well Name	Monitoring Zone	Isotope
BW02	SAS	Yes
MW01	SAS	Yes
MW04/R	SAS	Yes
MW06	SAS	Yes
MW07	SAS	Yes
MW14	SAS	Yes
MW17	SAS	Yes
MW20	SAS	Yes
MWAS	SAS	No
MWBS	SAS	Yes
MWDS	SAS	Yes
MW02	IAS	Yes
MW03	IAS	No
MW10	IAS	No
MW11	IAS	Yes
MW15	IAS	No
MW22	IAS	Yes
XDEPPBS	IAS	Yes
MWAI	IAS	Yes
MWCI	IAS	Yes
MW04R	IAS	Yes
XDEPFLD	UFA	Yes
XDEPPBD	UFA	Yes
MWBU	UFA	Yes
MWCU	UFA	No
MWDU	UFA	Yes
MWEU	UFA	Yes
SW01	Spring	Yes



Note:
Hatched areas indicate where the Upper Florida Aquifer (UFA), which is part of the Floridan Aquifer System (FAS), elevation is higher than the Surficial Aquifer System (SAS) water table elevation. Data based on USGS OFR 80406 report "Estimated potentiometric surface for the Tertiary limestone aquifer system, southeastern United States, prior to development."

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N

0 1.5 3 Miles

LEGEND

Springs
POT Contour
FAS > SAS WT
Wekiwa BMAP
Wekiwa PFA
County

Wells
Monitoring Zone
SAS
IAS
UFA
Spring

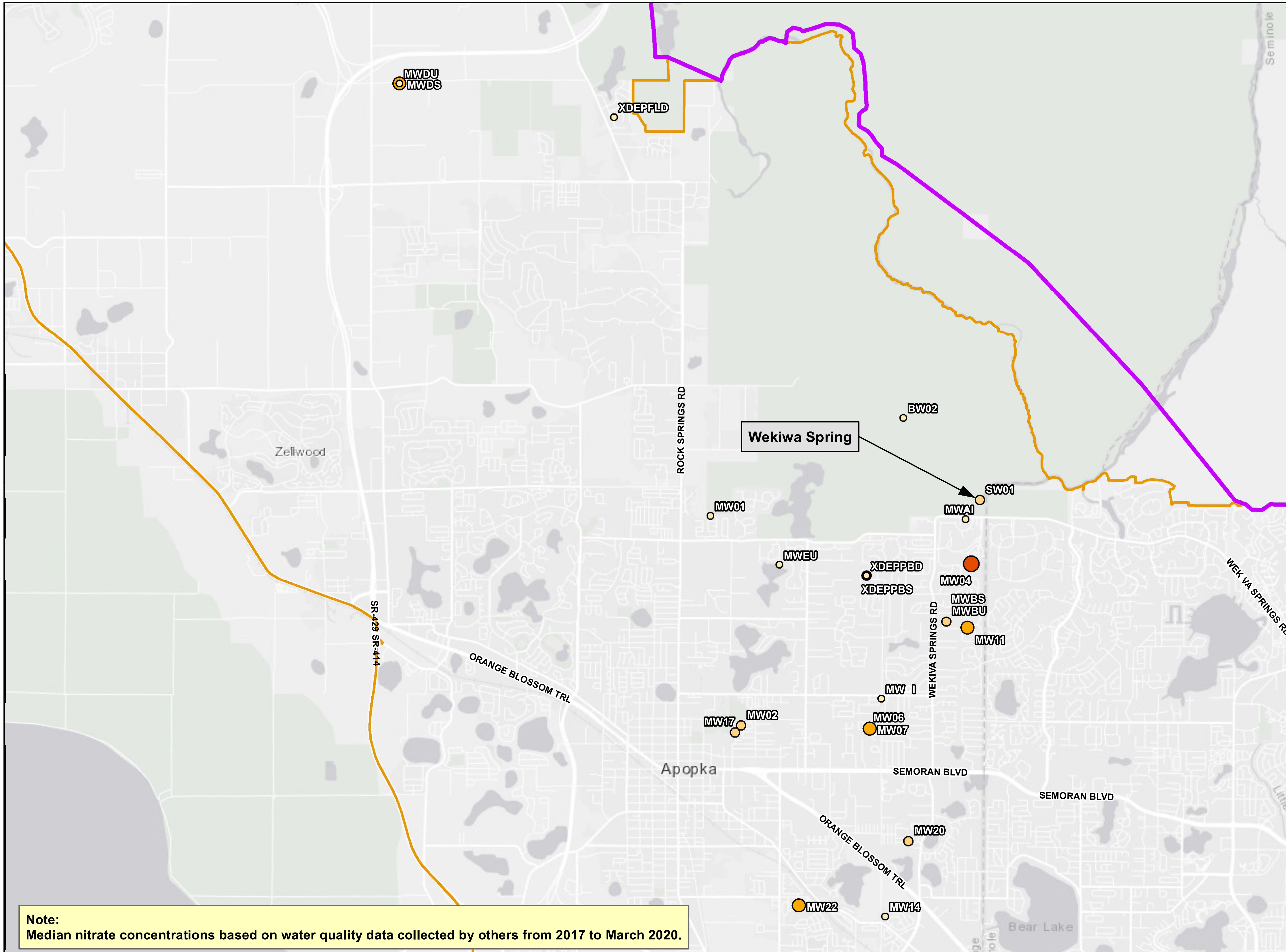
Head Difference SAS - UFA (ft)
High : 88
Low : 0

Sources:
Background: ESRI
Recharge: SJRWMD, 2016
Potentiometric Surface: FGS, 2017
SAS Head Diff: FDEP, 2019
Wells: Orange County, 2020

Exhibit
4

Hydraulic Head Difference Between SAS and UFA

Wekiwa BMAP Gap Analysis



Note:
Median nitrate concentrations based on water quality data collected by others from 2017 to March 2020.

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N

0 0.75 1.5 Miles

LEGEND

Wekiwa BMAP

Wekiwa Priority Focus Area

Groundwater Sampling Locations

Median Nitrate-N Conc

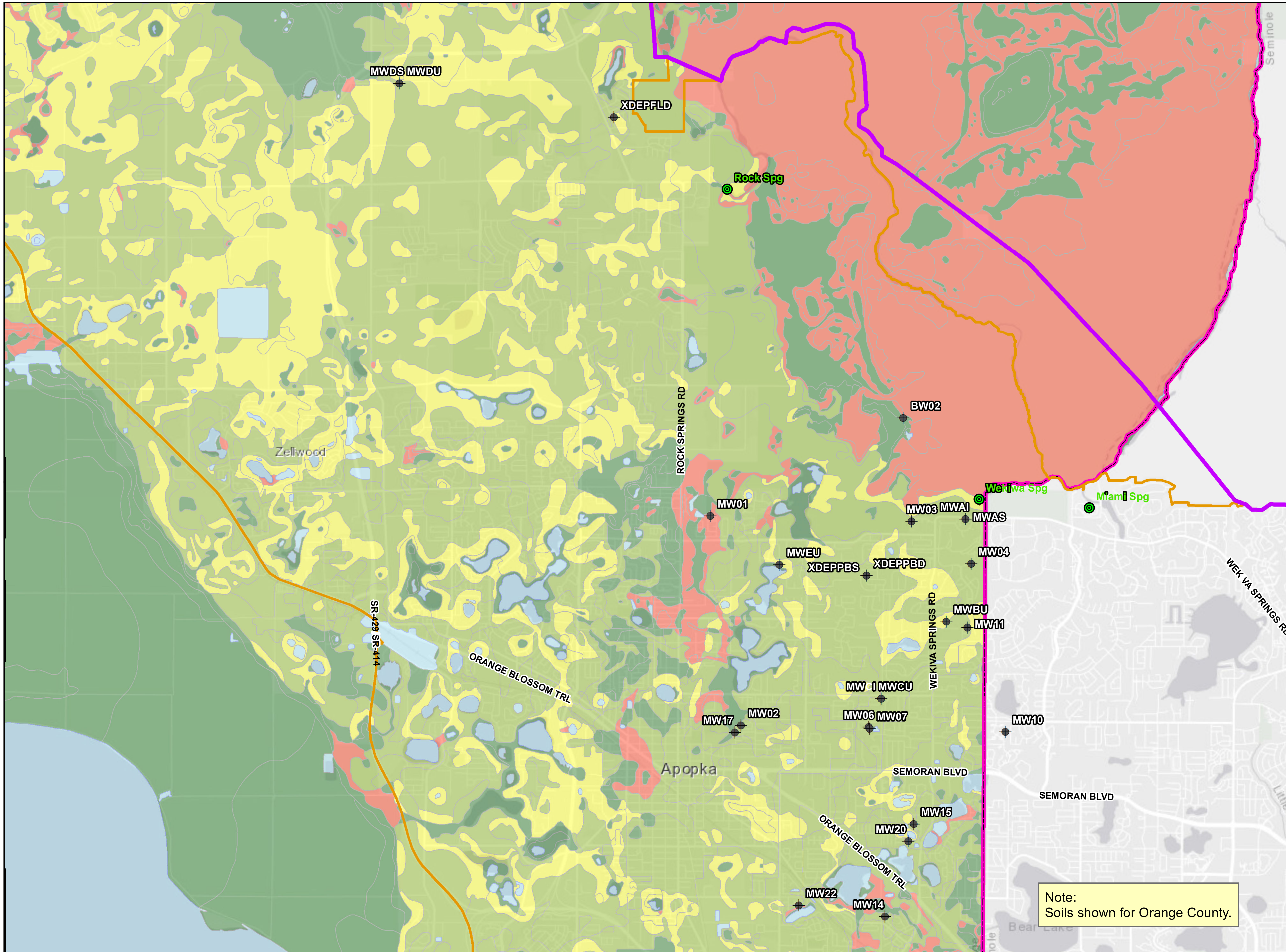
- <1 mg/L
- 1 mg/L
- 2 mg/L
- 9 mg/L

Sources:
Background: ESRI
Recharge: SJRWMD, 2016
Potentiometric Surface: FGS, 2017
Wells: Orange County, 2020

Exhibit
5

Wekiwa Sampling Locations and Nitrate Concentration

Wekiwa BMAP Gap Analysis



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N

0 0.75 1.5 Miles

LEGEND

- Springs
- Wekiwa BMAP
- Wekiwa Priority Focus Area
- Orange County
- Groundwater Sampling Locations

Runoff Potential

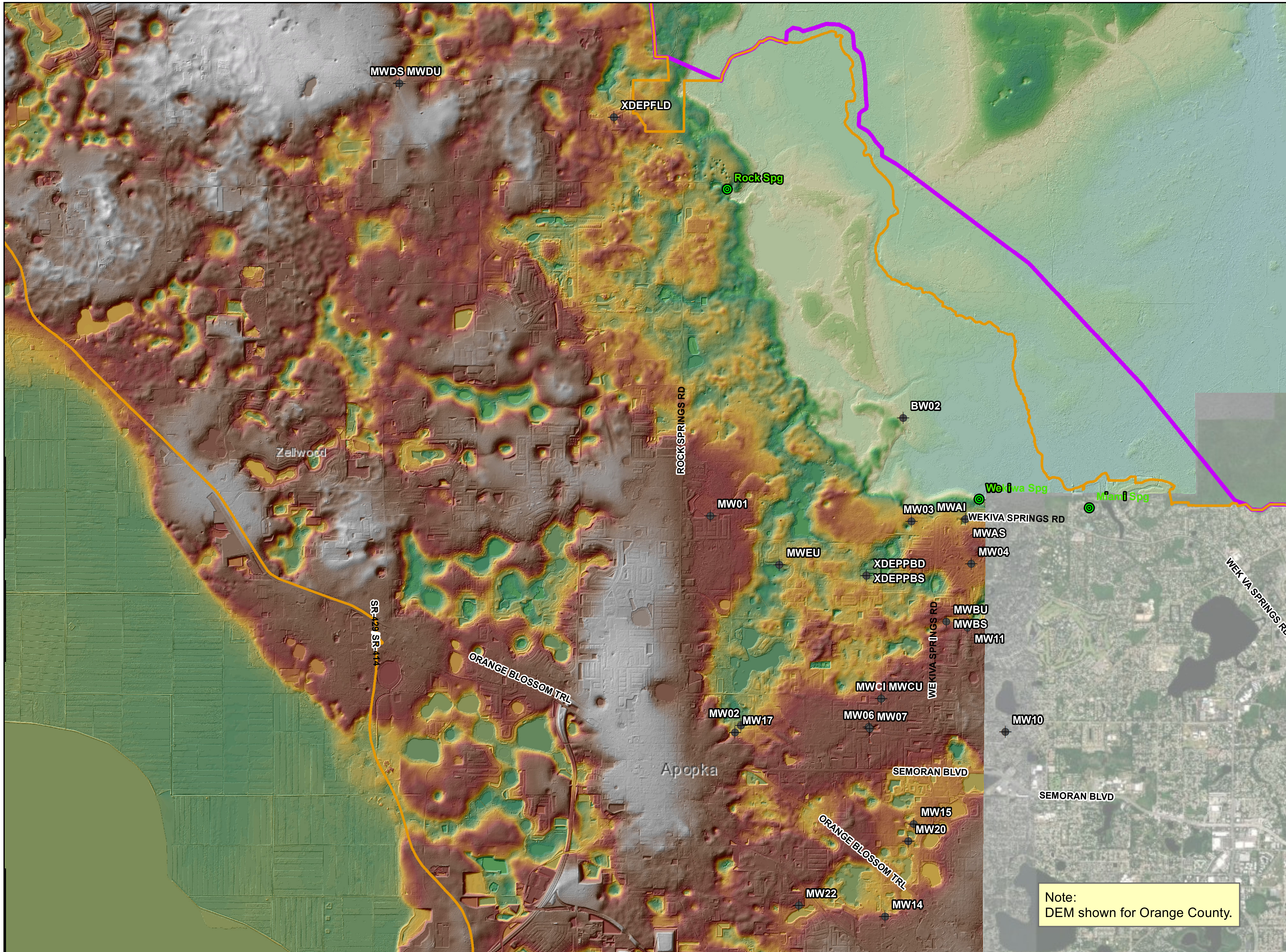
- Null / Water
- Negligible
- Very low
- Low
- High
- Very high

Sources:
Background: ESRI
Soils: NRCS, 2013
Wells: Orange County, 2020

Exhibit
6

Existing Soils by Runoff Potential

Wekiwa BMAP Gap Analysis



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N

0 0.75 1.5 Miles

LEGEND

Springs

Wekiwa Priority Focus Area

Wekiwa BMAP

localnam

Groundwater Sampling Locations

DEM (ft. NAVD88)

Value

High : 186.977

Low : 9

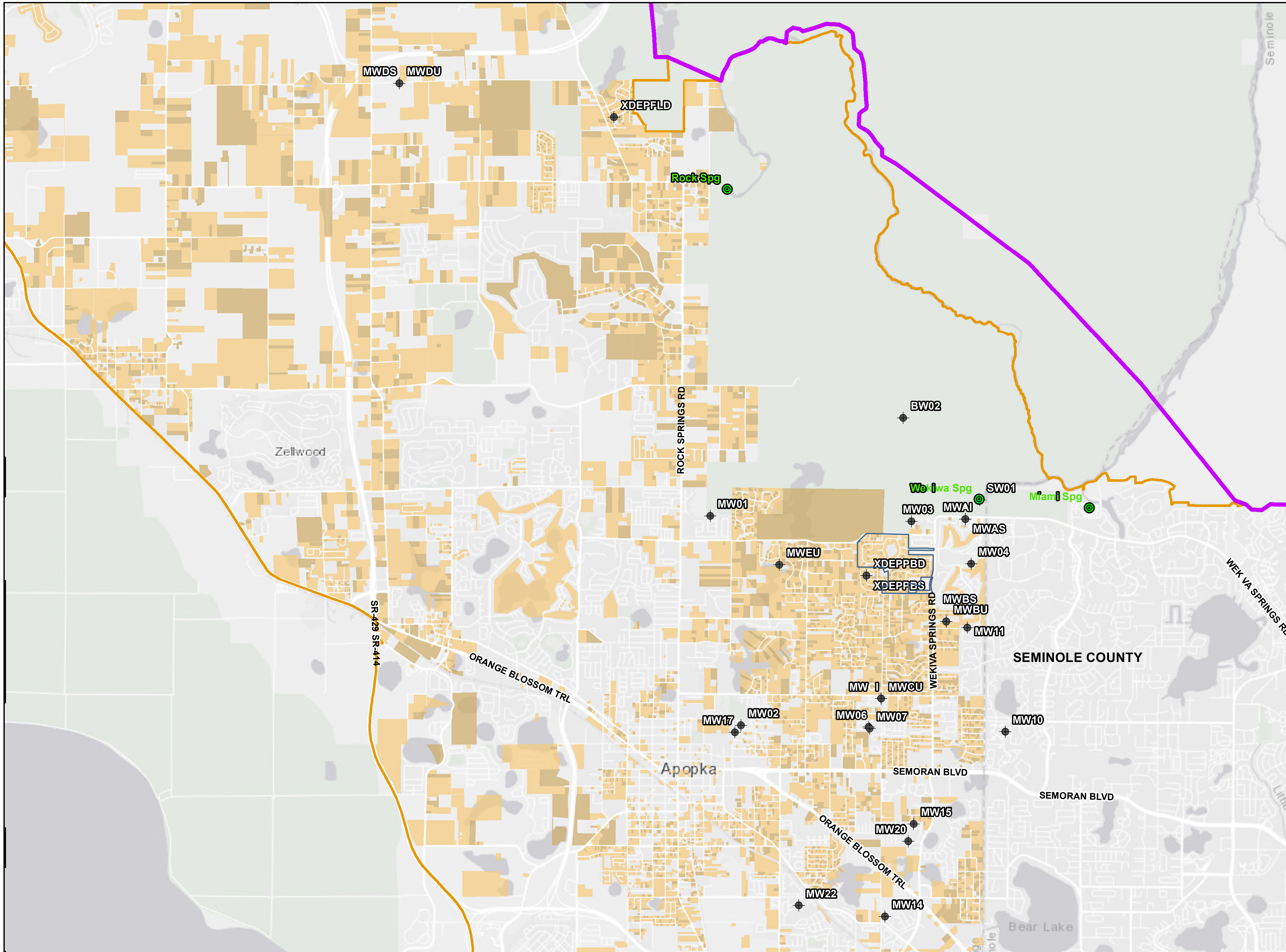
Sources:
Background: ESRI
DEM: Orange County, 2008
Wells: Orange County, 2020

Exhibit

7

Digital Elevation Map

Wekiwa BMAP Gap Analysis



N

0 0.75 1.5 Miles

LEGEND

- Springs
- Septic to Sewer Retrofit Y21-738
- Groundwater Sampling Locations
- Wekiwa BMAP
- Wekiwa Priority Focus Area

Parcels with Septic

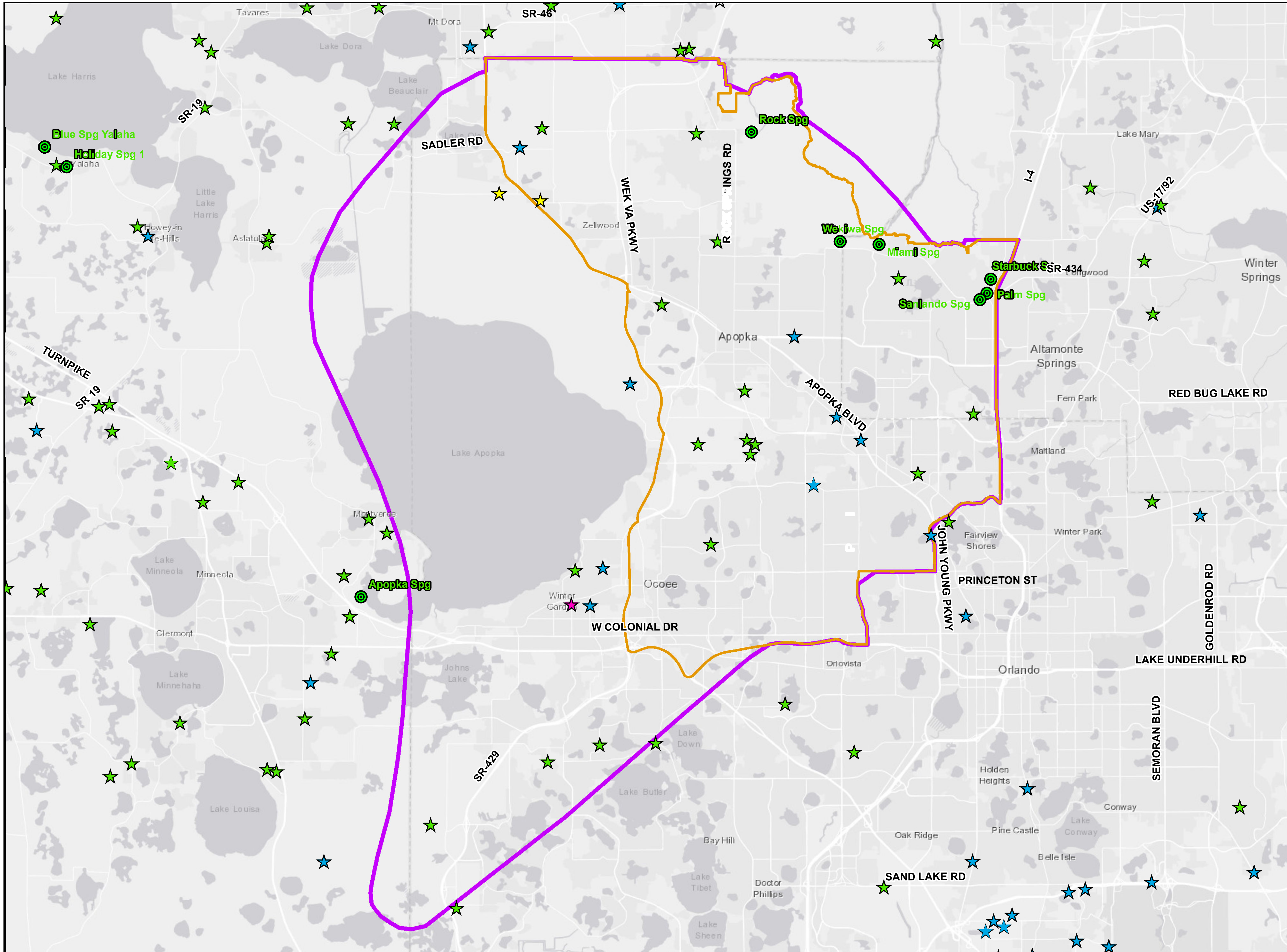
- Known Septic
- Likely Septic

Sources:
Background: ESRI
Septic: FDOH, 2017
Wells: Orange County, 2020

Exhibit
8

Septic Locations

Wekiwa BMAP Gap Analysis



N

0 2.5 5 Miles

LEGEND

Wastewater Facility Type

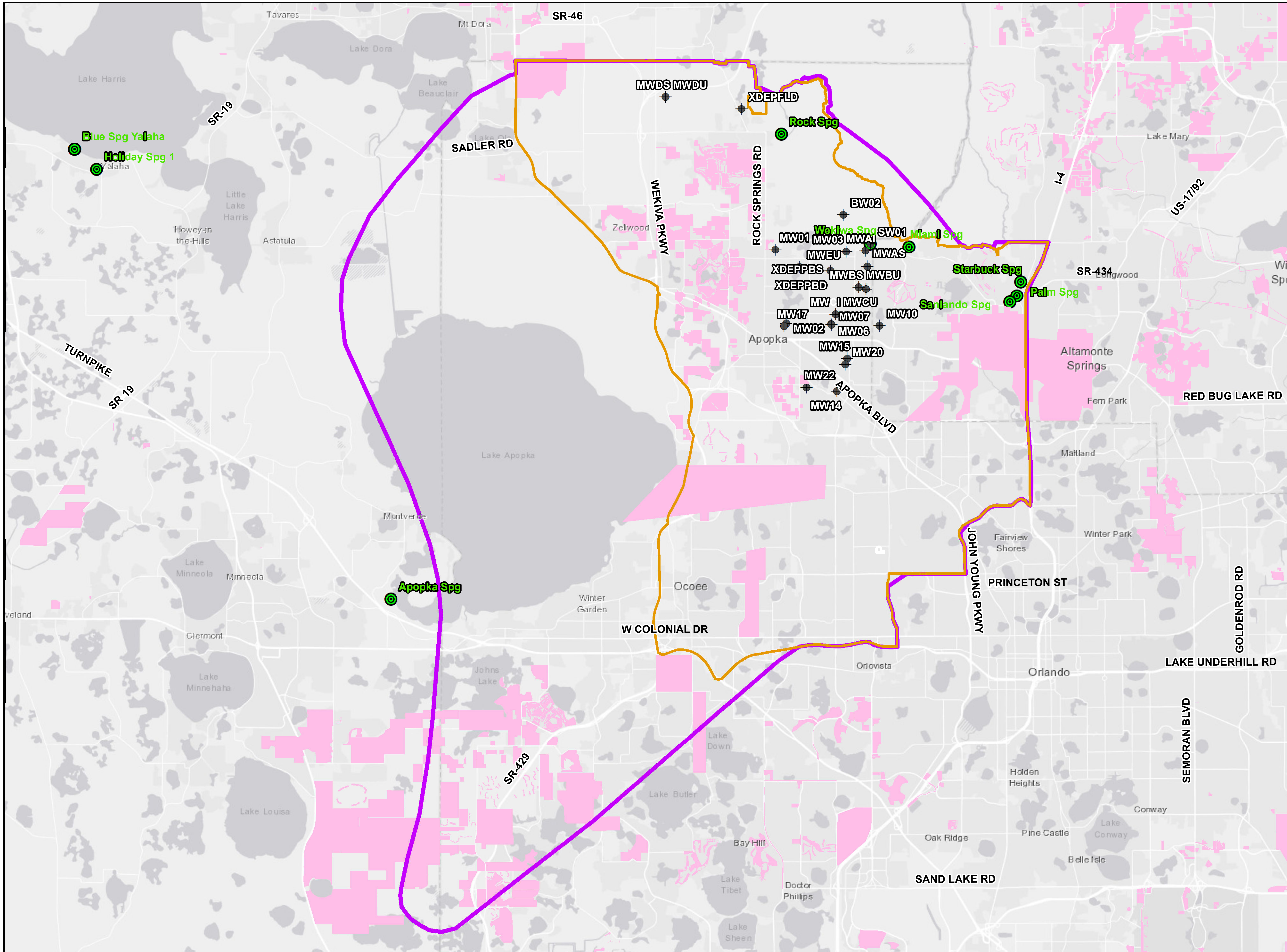
- Domestic Wastewater
- Industrial Water
- Petroleum Cleanup
- Residuals Septage Management
- Springs
- Wekiwa Priority Focus Area
- Wekiwa BMAP

Sources:
Background: ESRI
Wastewater Facilities: FDEP, 2020
Springs: FDEP, 2020

Exhibit
9

Wastewater Facilities

Wekiwa BMAP Gap Analysis



N

0 2.5 5 Miles

LEGEND

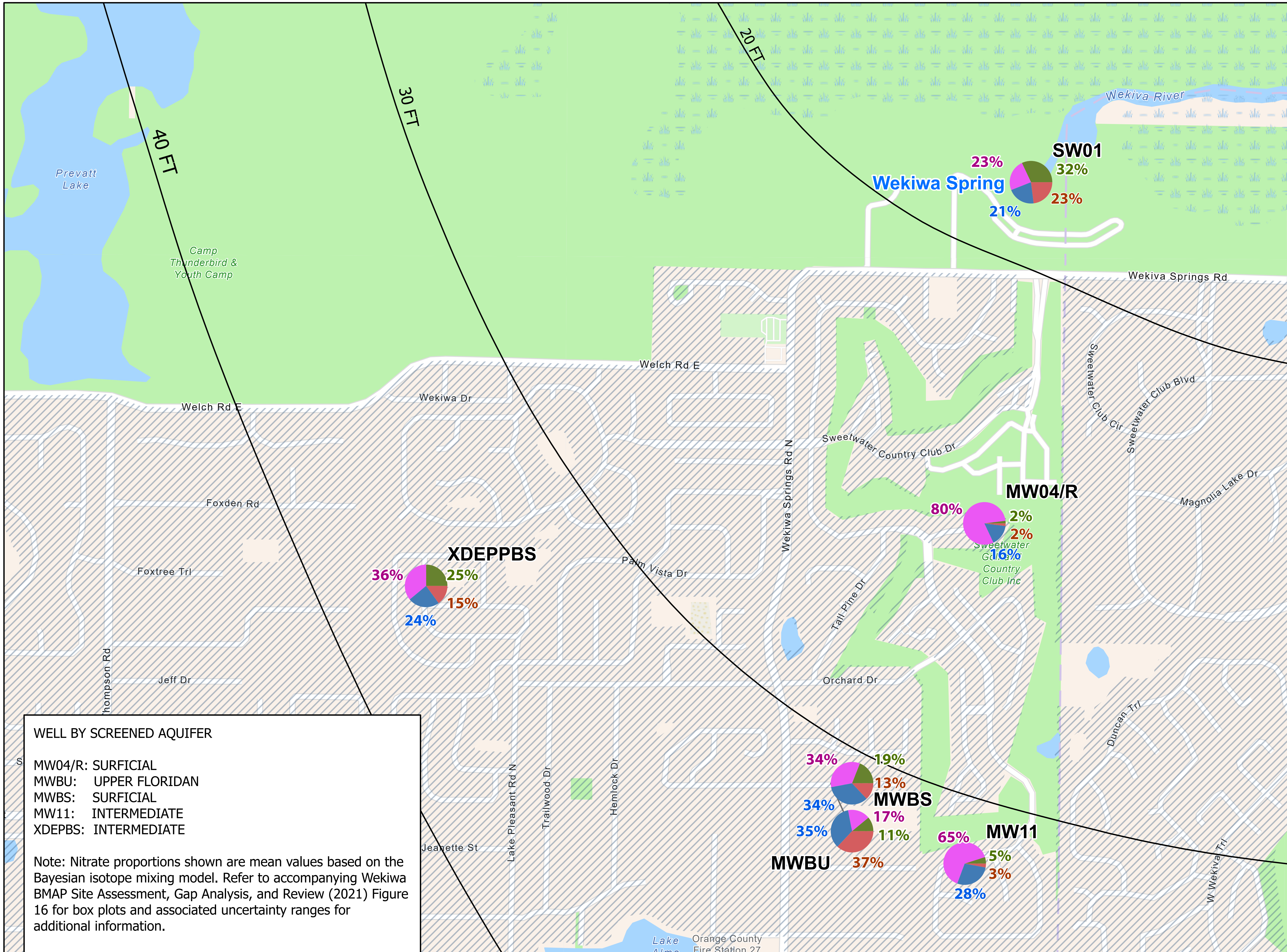
- Wekiea Priority Focus Area
- Wekiwa BMAP
- Reclaimed Water Areas
- Groundwater Sampling Locations
- Springs

Sources:
Background: ESRI
Reclaimed Water: SJRWMD
Springs: FDEP, 2020

Exhibit
10

Reuse Water Map

Wekiwa BMAP Gap Analysis



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0 500 1,000 Feet

Residential Land Use

Well Identifier

Nitrate Fertilizer Proportion

Ammonia/Urea Fertilizer Proportion

Sewage & Manure Proportion

Denitrification Proportion

Potentiometric Contour

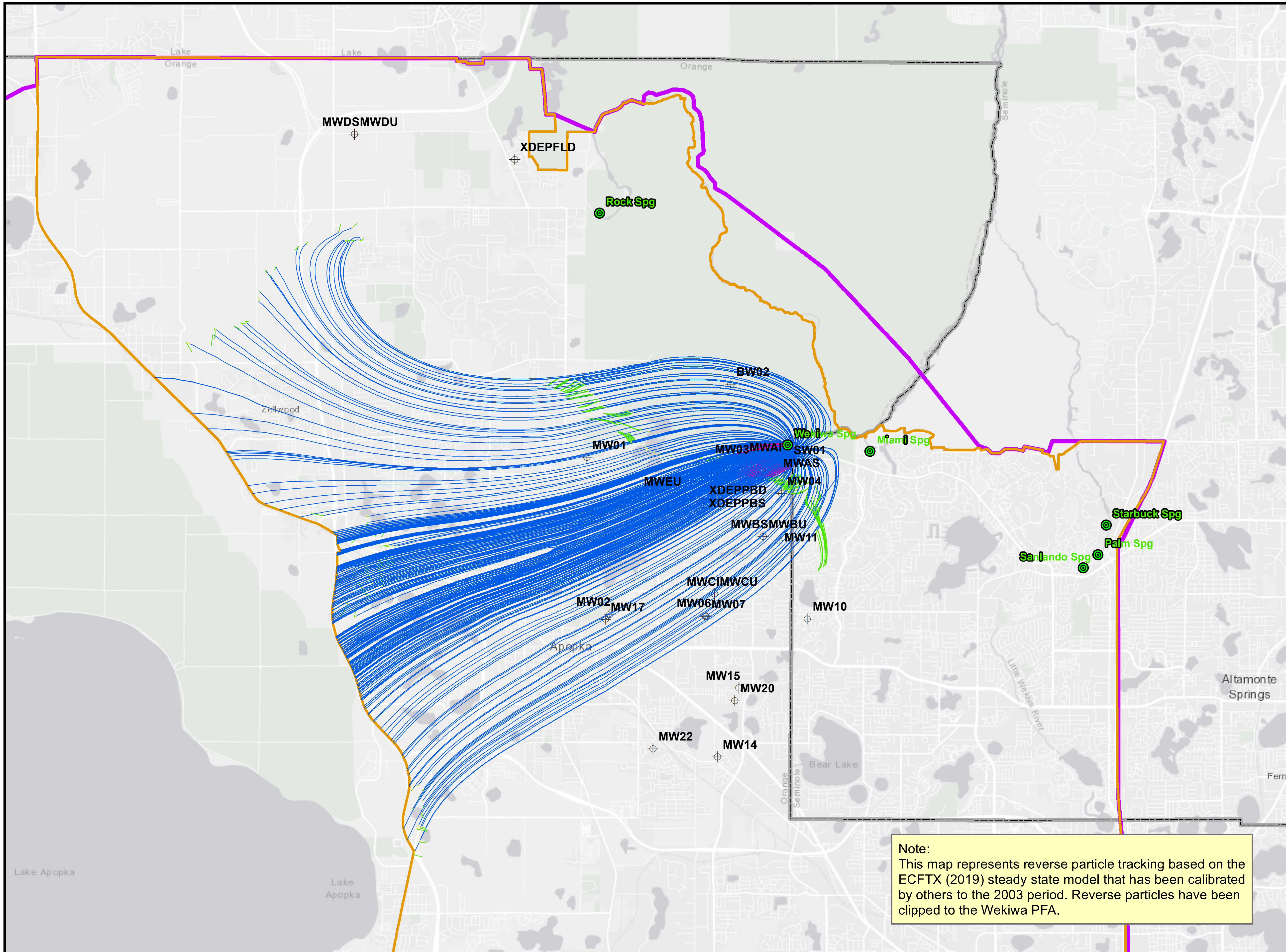
Sources
Nitrate Source Allocations: SIAR Model (Drummond Carpenter, 2021)
Potentiometric Surface: FGS, 2017 (NAVD88)
Aerial: Orange County, 2020
Wells: Orange County, 2020
Basemap: ESRI

Exhibit

11

Sources of Nitrate in the Aquifers

Wekiwa BMAP Gap Analysis



Note:
This map represents reverse particle tracking based on the ECFTX (2019) steady state model that has been calibrated by others to the 2003 period. Reverse particles have been clipped to the Wekiwa PFA.

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N

0 1 2 Miles

LEGEND

- Springs

Particle Tracking Hydrogeologic Unit

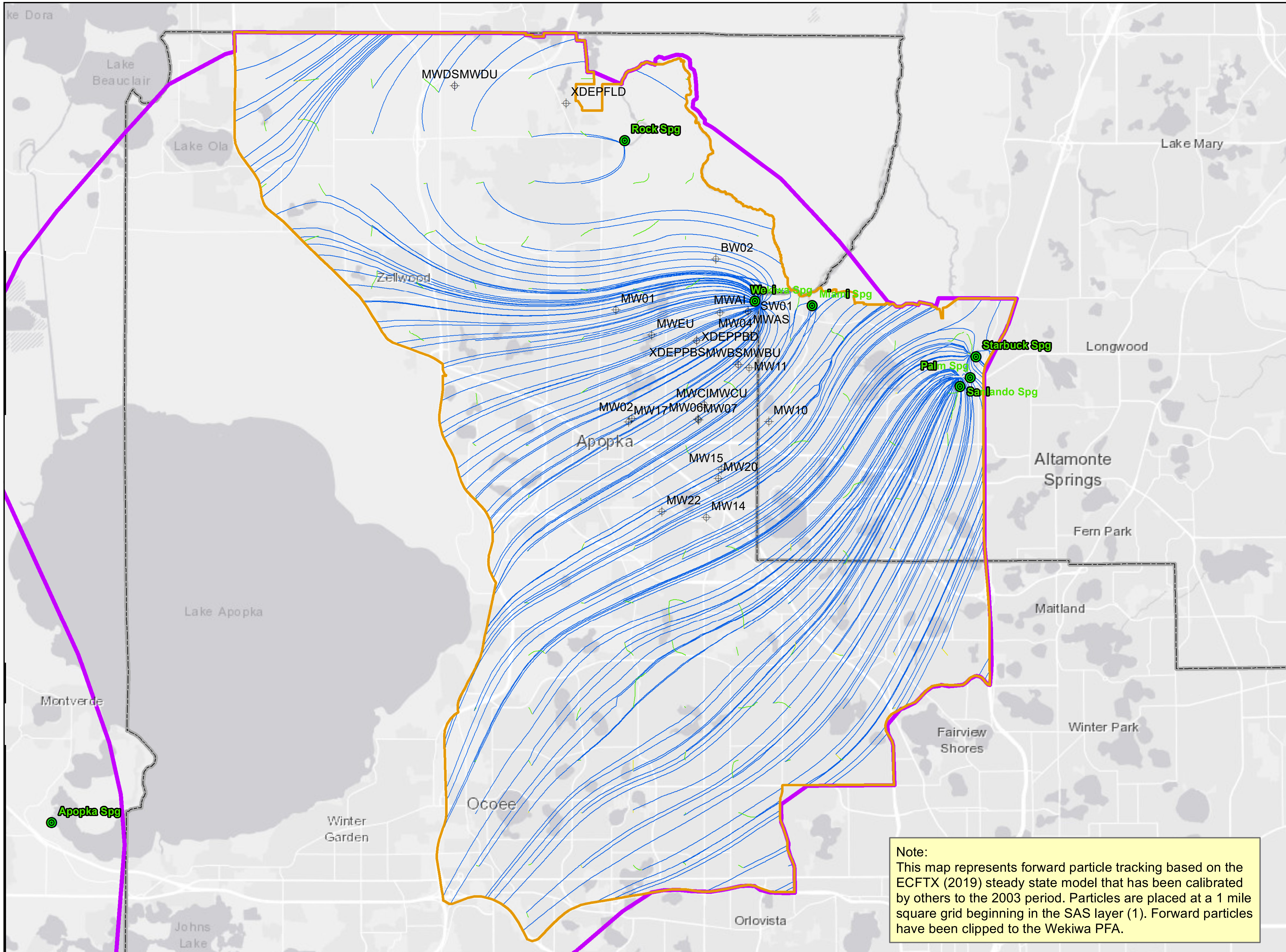
- 1 - SAS
- 2 - IAS
- 3 - UFA
- 4 - UFA
- 5 - UFA
- 6 - MCU
- Wekiwa Study Sampling Locations
- Wekiwa Priority Focus Area
- Wekiwa BMAP
- Orange County

Sources:
Background: ESRI
Roads: Orange County Boundary, 2017
Wekiwa BMAP: FDEP, 2018
Wekiwa PFA: FDEP, 2019
GW Travel Time: FDEP, 2015

Exhibit
12

Wekiwa BMAP ECFTX Reverse Partical Tracking

Wekiwa BMAP Gap Analysis



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N

0 1.5 3 Miles

LEGEND

- Springs
- Wekiwa Study Sampling Locations
- Wekiwa Priority Focus Area
- Wekiwa BMAP

Particle Tracking Hydrogeologic Unit

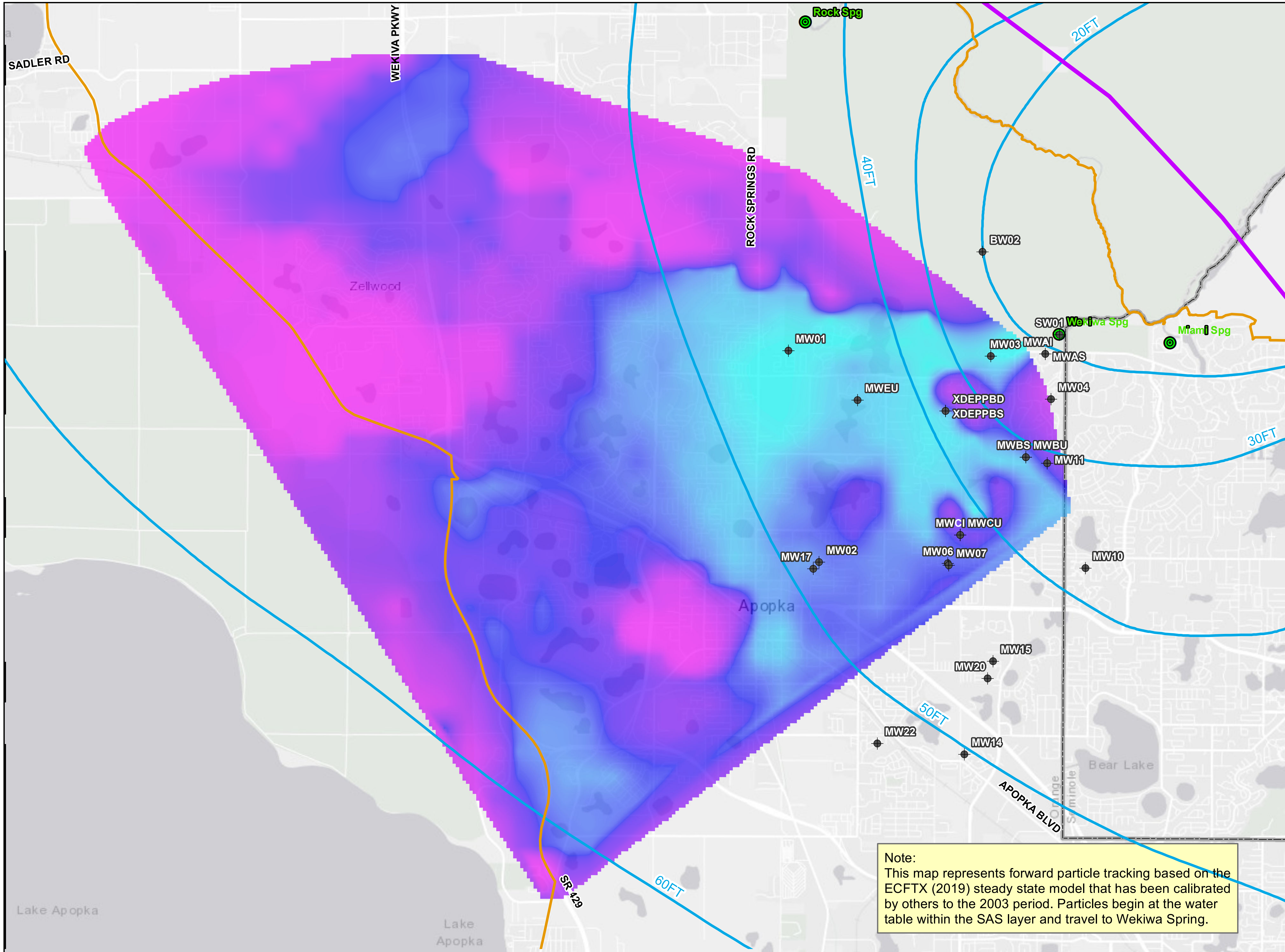
- 1 - SAS
- 2 - IAS
- 3 - UFA
- 4 - UFA
- 5 - UFA
- 6 - MCU
- Orange County

Sources:
Background: ESRI
Roads: Orange County Boundary, 2017
Wekiwa BMAP: FDEP, 2018
Wekiwa PFA: FDEP, 2019
GW Travel Time: FDEP, 2015

Exhibit
13

Wekiwa BMAP ECFTX Forward Partical Tracking

Wekiwa BMAP Gap Analysis

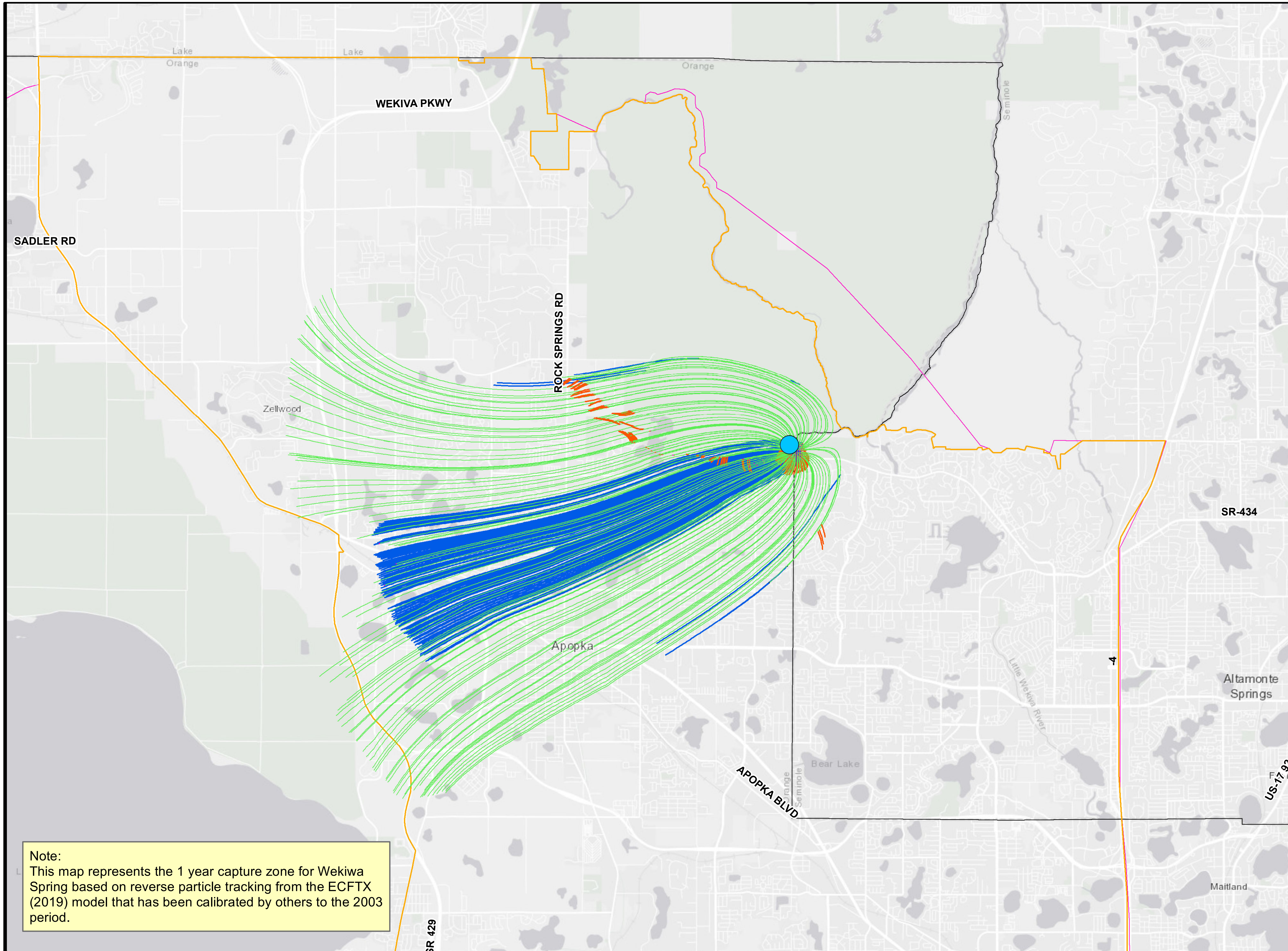


Exhibit

14

Wekiwa PFA ECFTX Groundwater Travel Time

Wekiwa BMAP Gap Analysis



Note:
This map represents the 1 year capture zone for Wekiwa Spring based on reverse particle tracking from the ECFTX (2019) model that has been calibrated by others to the 2003 period.

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N

0 1 2 Miles

LEGEND

- Wekiwa Spring
- Wekiwa BMAP
- Spring Priority Focus Area
- Orange County

Hydrogeologic Unit

- SAS
- IAS
- UFA (Ocala, permeable zone)
- UFA (Ocala, unpermeable zone)
- UFA (Avon Park, permeable zone)
- MCU

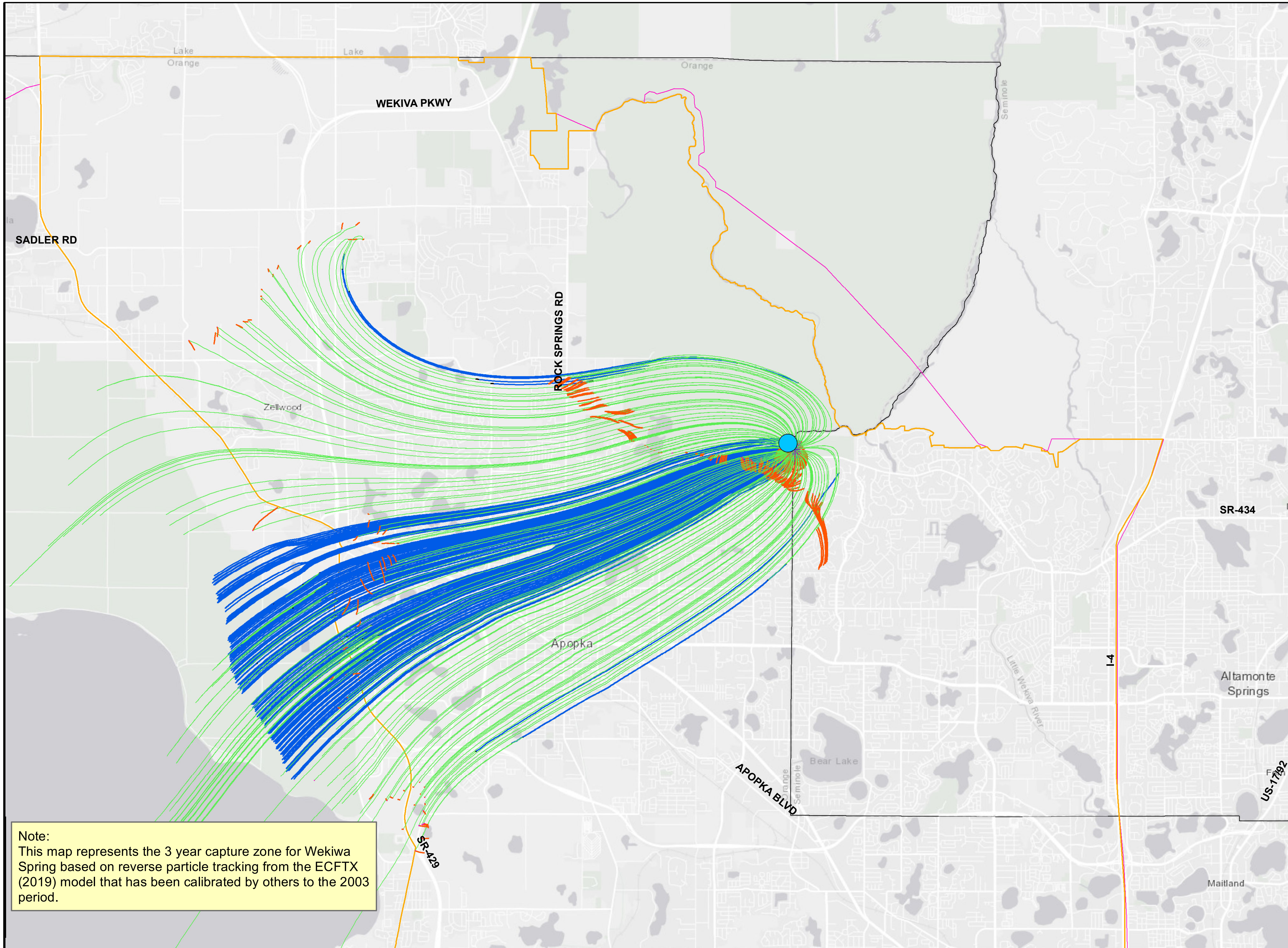
Sources:
Background: ESRI
Capture Zone: ECFTx Model, 2019
Wekiwa BMAP: FDEP, 2018
Wekiwa PFA: FDEP, 2019

Exhibit

15

Wekiwa Spring Capture Zone 1 year

Wekiwa BMAP Gap Analysis



Note:
This map represents the 3 year capture zone for Wekiwa Spring based on reverse particle tracking from the ECFTX (2019) model that has been calibrated by others to the 2003 period.

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N

0 1 2
Miles

LEGEND

- Wekiwa Spring
- Wekiwa BMAP
- Spring Priority Focus Area
- Orange County

Hydrogeologic Unit

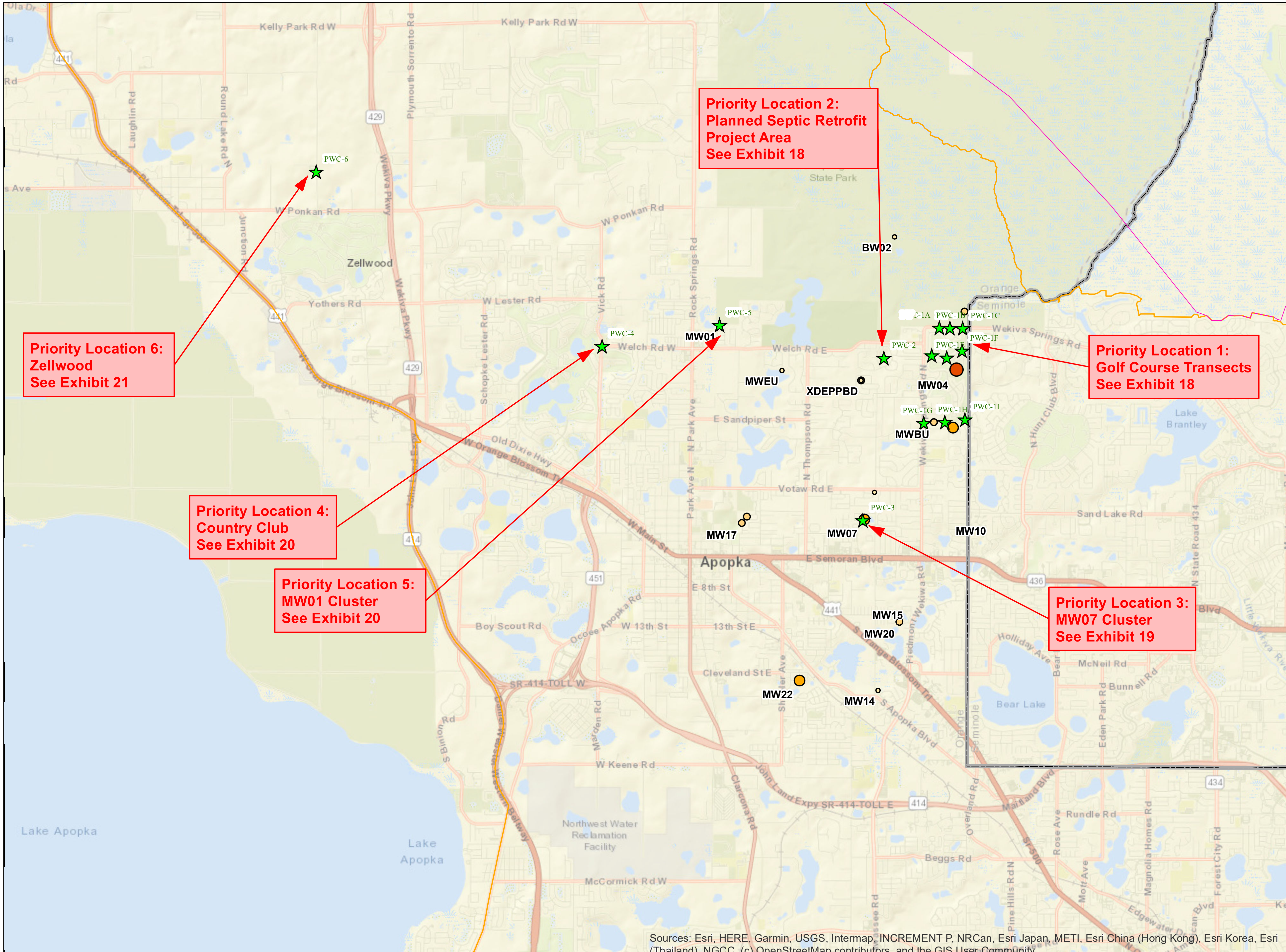
- SAS
- IAS
- UFA (Ocala, permeable zone)
- UFA (Ocala, unpermeable zone)
- UFA (Avon Park, permeable zone)
- MCU

Sources:
Background: ESRI
Capture Zone: ECFTx Model, 2019
Wekiwa BMAP: FDEP, 2018
Wekiwa PFA: FDEP, 2019

Exhibit
16

Wekiwa Spring Capture Zone 3 year

Wekiwa BMAP Gap Analysis



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N

0 0.75 1.5 Miles

LEGEND

- Proposed Well Cluster
- Wekiwa BMAP
- Spring Priority Focus Area
- Orange County

Median Nitrate-N Concentration

- <1 mg/L
- 1 mg/L
- 2 mg/L
- 9 mg/L

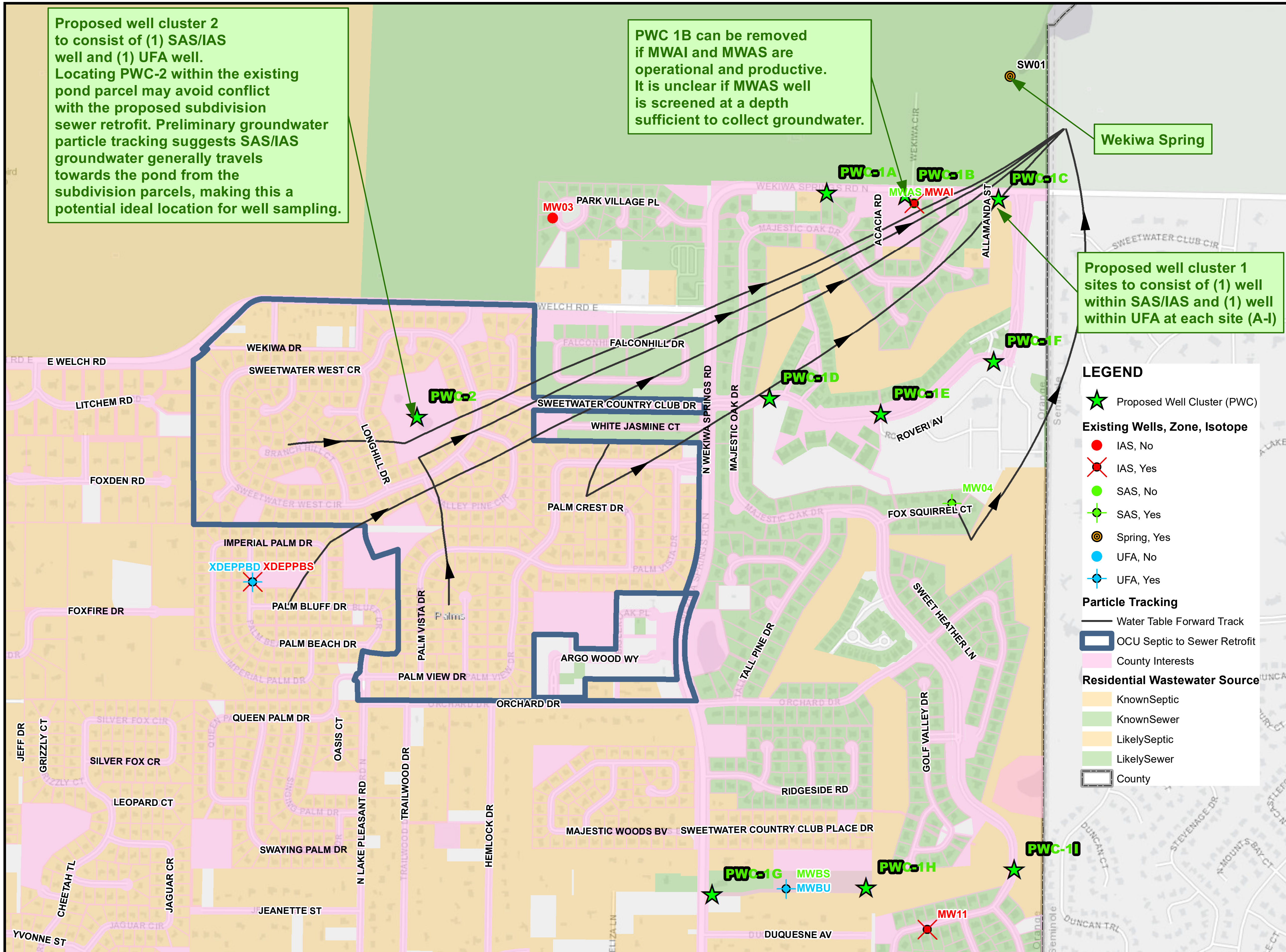
Sources:
Background: ESRI
Wells: Orange County (2020)

Exhibit

17

Recommended Well Cluster Locations Map

Wekiwa BMAP Gap Analysis



N

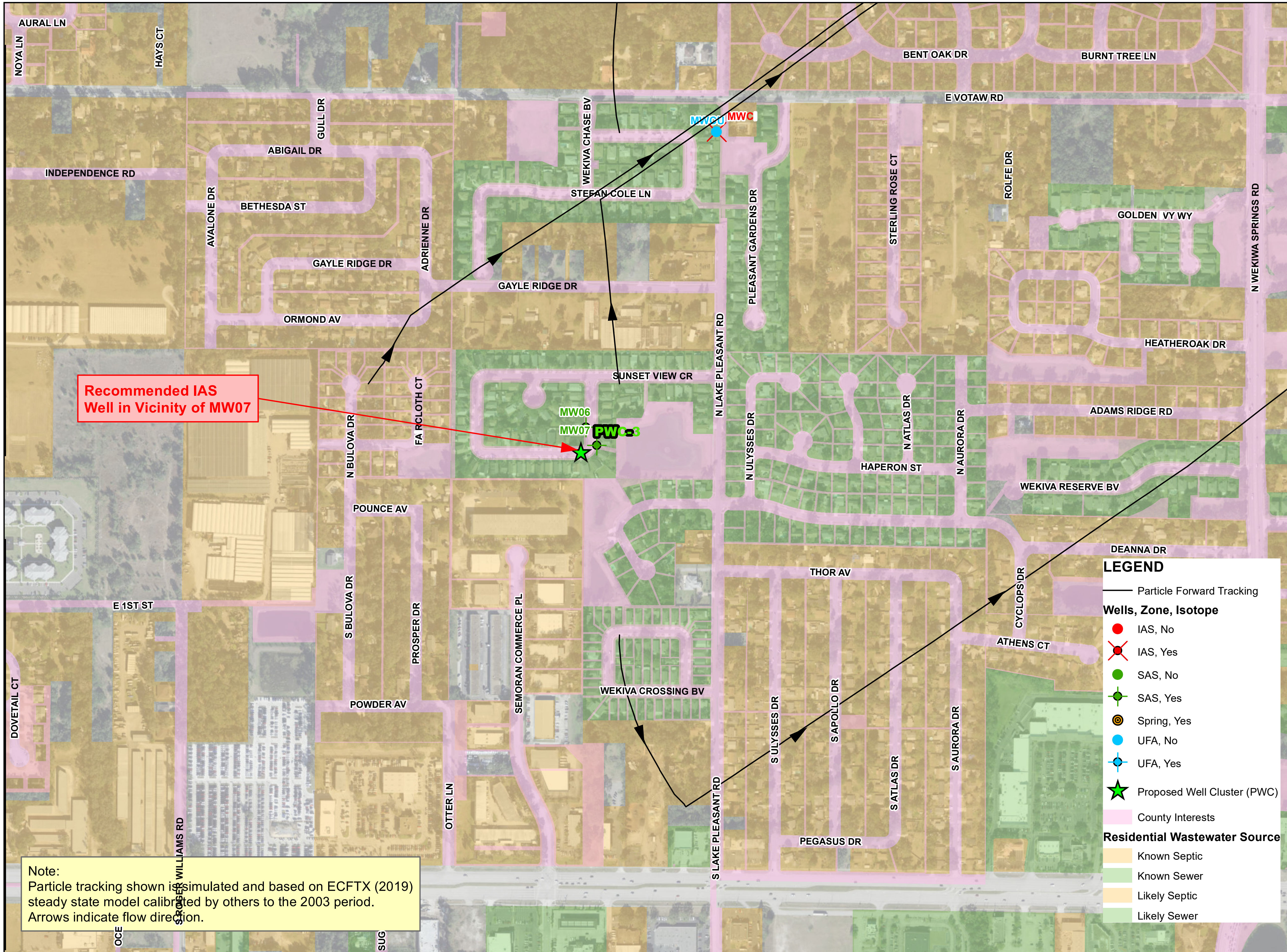
0 500 1,000 Feet

Sources:
Background: ESRI
Roads: Orange County, 2017
Septic: FDOH, 2017
Wells: Orange County, 2020
Particle Tracking: ECFTX (2019)
Retrofit: Orange County (2020)

Exhibit 18

Priority Location 1A-1I & 2 Sweetwater Golf and Country Club & Planned Septic to Sewer Retrofit

Wekiwa BMAP Gap Analysis



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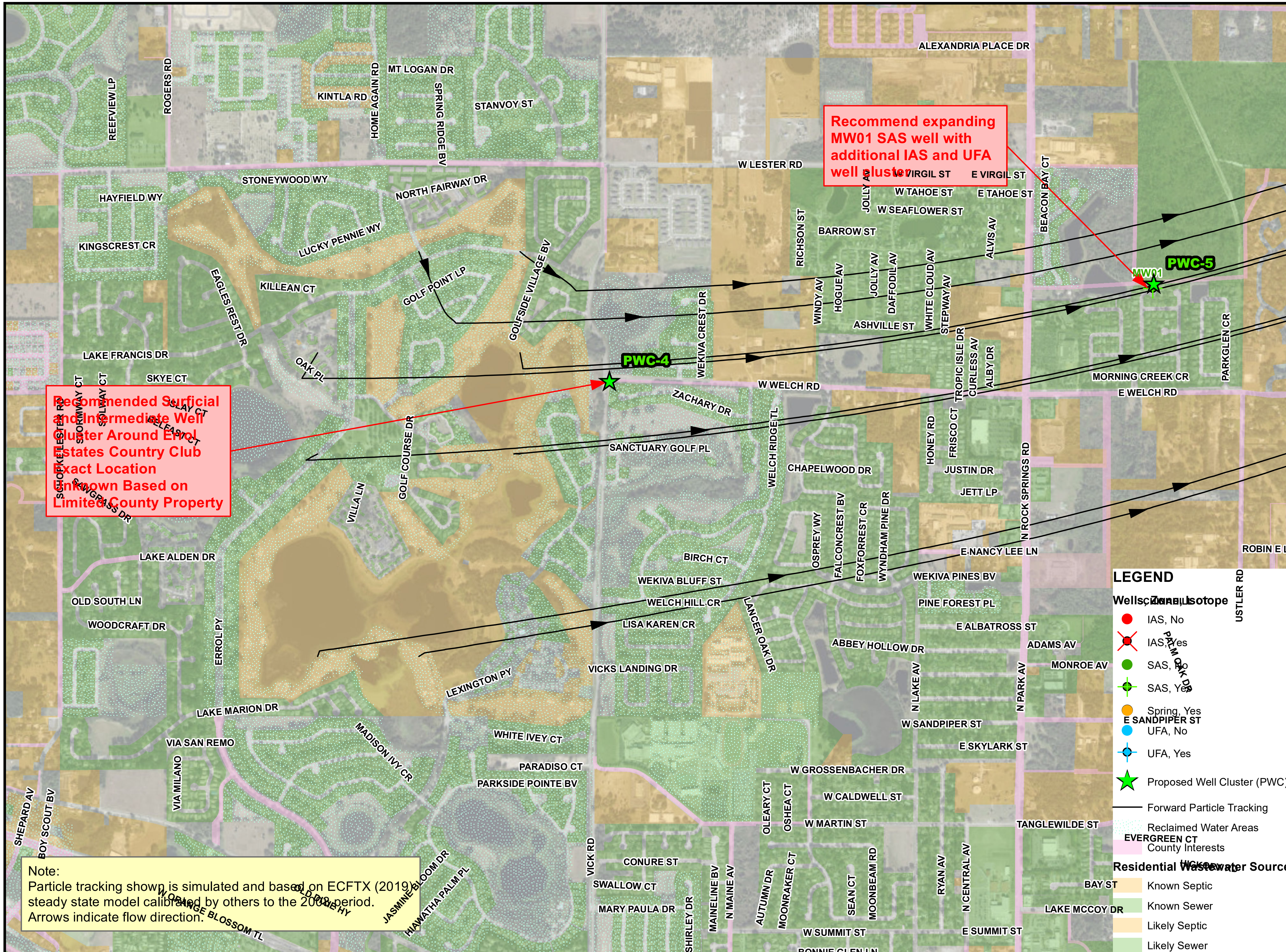
Sources:
Background: ESRI
Roads: Orange County (2017)
Septic: FDOH (2017)
Wells: Orange County (2020)
Particle Tracking: ECFTX (2019)
Retrofit: Orange County (2020)

Exhibit 19

Priority Location 3 MW07 Well Cluster Recommendations

Wekiwa BMAP Gap Analysis



N

0 1,000 2,000 Feet

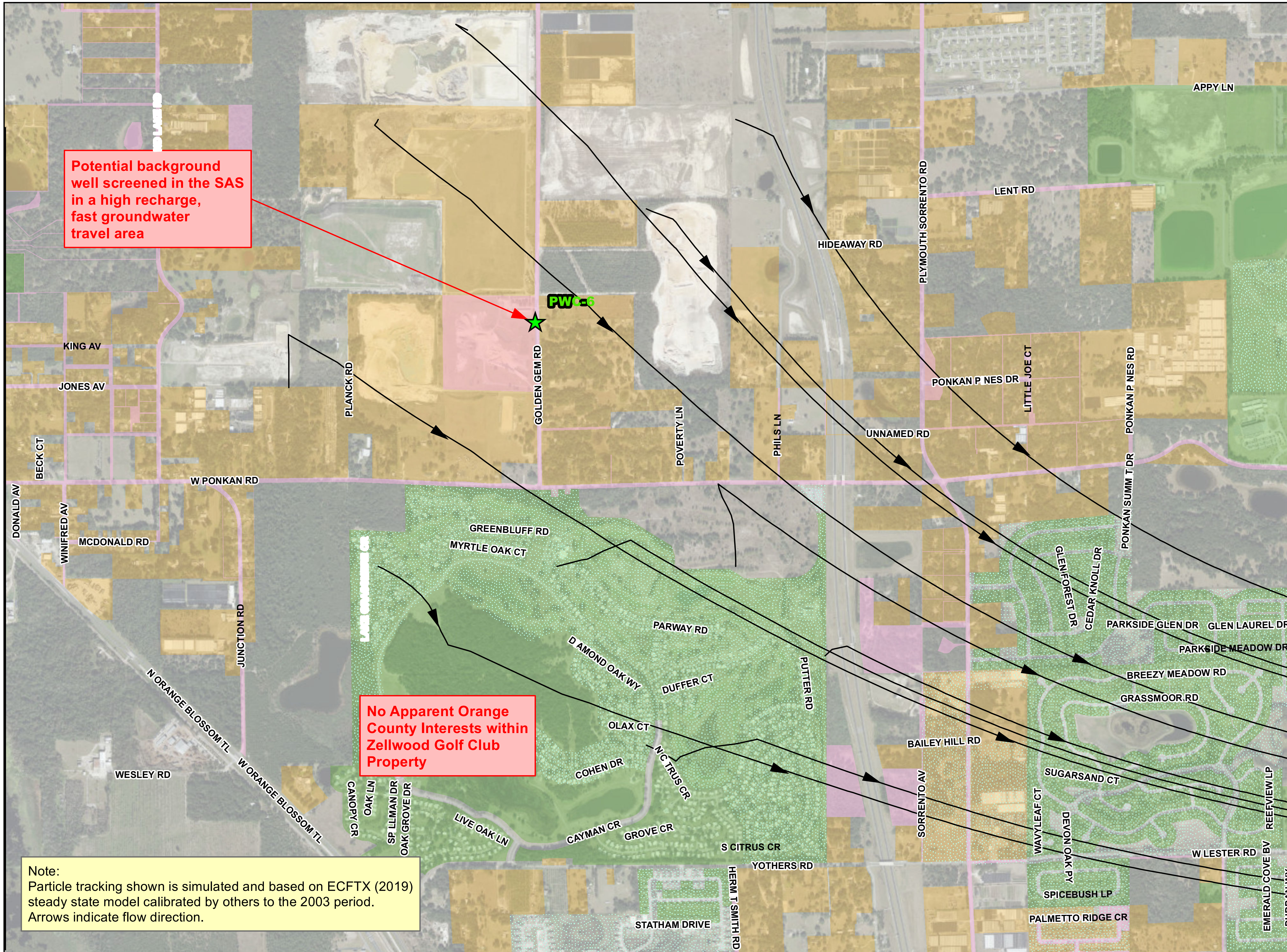
Sources:
Background: ESRI
Roads: Orange County, 2017
Reclaimed Water: SJRWMD
Wells: Orange County, 2020
Particle Tracking: ECFTX (2019)
Retroft: Orange County (2020)
Septic: FDOH (2017)

Exhibit

20

Priority Location 4 & 5
Country Club
Well Cluster
Recommendations

Wekiwa BMAP Gap Analysis



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N

0 1,000 2,000 Feet

LEGEND

- Forward Particle Tracking
- Proposed Well Cluster (PWC)
- Reclaimed Water Areas
- County Interests

Residential Wastewater Source

- Known Septic
- Known Sewer
- Likely Septic
- Likely Sewer

Sources:
Background: ESRI
Roads: Orange County, 2017
Reclaimed Water: SJRWMD
Wells: Orange County, 2020
Particle Tracking: ECFTX (2019)
Retrofit: Orange County (2020)

Exhibit
21

Priority Location 6 Zellwood Well Cluster Recommendations

Wekiwa BMAP Gap Analysis