

Nitrogen Contributions of Karst Seepage into the Upper Floridan Aquifer from Sinking Streams and Sinking Lakes in the Wakulla Springshed

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Porter Hole Sink, Lake Jackson (Seán McGlynn, 2000)

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Abstract

This study revises estimates in the 2014 Nitrogen Source Inventory Loading Tool (NSILT) study produced by the Florida Department of Environmental Protection of total nitrogen loadings to Wakulla Springs and the Upper Wakulla River for sinking water bodies based on evaluating flows and water quality data for sinking streams and sinking lakes which were not included in the NSILT. Our results increase the total nitrogen loading estimate for sinking streams and lakes to the Upper Floridan Aquifer in the Wakulla Springshed from 10% to 17% making these the second largest source of nitrogen loading that can be remediated in the Wakulla Springshed after septic tanks.

Flows for the sinking streams and lakes were underestimated in the NSILT study by at least a factor of two because at the time there was no data on many of these sinking waterbodies. The Northwest Florida Water Management District, cooperating with Wakulla County, installed hydrological stations with metered stage, rainfall, flow, and other water quality data on most of the significant streams and lakes in the springshed. This new data allowed the calculation of seepage rates, for the first time, for many of these waterbodies. This study evaluates water quality and hydrologic conditions for seven sinking lake systems (listed in declining order by size): Lafayette (assorted compartments), Miccosukee, Munson, Iamonia, Jackson, Bradford Brook Chain of Lakes (BBCL), and Killlearn Chain of Lakes (KCOL).

Our analysis also shows that the sinking waterbodies contribute significantly to the impairment of the water quality of Wakulla Spring and the Upper Wakulla River. These loadings are almost evenly split, 51% for the sinking lakes and 49% for the sinking streams. These findings suggest that the sinking waterbodies, in the Wakulla Springshed, contribute 17% of the total nitrogen load to the Springshed. Their protection and restoration should be a remediation priority in the next revision of the Basin Management Action Plan since they will be the largest nitrogen source contributor when the septic tank problem is solved.

However, the three largest sources, which comprise 66% of the annual loadings of total nitrogen, are waterbodies which receive little direct discharge of nitrogen from human sources: Lost Creek, Lake Iamonia, and Fisher Creek. These findings suggest that remediating urban storm water loadings to the large urban lakes, i.e. Jackson, Lafayette, and Munson, which contribute 20% of the total nitrogen loadings from the sinking waterbodies, should be a remediation priority in the next revision of the Basin Management Action Plan for restoring water quality in the Upper Wakulla River and Wakulla Springs Basin

Introduction

Karst geology is quite common and is found on twenty five percent of the Earth's surface. However, the Wakulla Springshed is unusual. It has the necessary physical processes of hydrology and geology that allow a variety of karst features. The Wakulla Springshed is one of the few places with all the types of Karst features. In this report we are concerned with sinking waterbodies and their effects on Wakulla Springs.

This project expands the analysis of the nitrogen loading budget for the Wakulla Spring and Upper Wakulla River Basin Management Action Plan (FDEP, 2015) by estimating seepage into ground water from sinking lakes and wet sinkholes within the Lakes Region of the Wakulla Springshed (see map 1). The 2014 Florida Department of Environmental Protection (FDEP) Nitrogen Source Inventory and Loading Tool (NSILT) study (Eller and Katz, 2014) estimates the nitrogen loading to the Upper Florida Aquifer (UFA) from seven sources: Septic Tanks, Wastewater Treatment Facilities, Atmospheric Deposition, Livestock, Farm Fertilizers, Urban Fertilizers, and Sinking Streams. This project expands the 'Sinking Streams' category to include sinking lakes, and changes the category label to 'Sinking Waterbodies.'

The Wakulla Springshed is located in the eastern Panhandle of Florida (Gadsden, Jefferson, Leon, and Wakulla Counties) and southern coastal plain of Georgia, please see map 1. Ground elevations range from sea level along the Florida coastline to a maximum elevation of about 139 feet above mean sea level in the northwest corner of Gadsden County, Florida, and in the northern portion of the three Georgia counties. The median annual rainfall in the Wakulla Springshed from 1968 to 2010 was 62.2 in/yr, based on a springshed area of 1,569 square miles and a median annual rain at 4,650 MGD (FSI, 2011). Evapotranspiration for this portion of Florida can be estimated at about 42 in/yr (1.06 m/yr) or about 3,120 MGD (4,825 cfs), for an estimated net precipitation in the springshed of about 20 in/yr (0.51 m/yr) or about 1,530 MGD (2,375 cfs).

The Wakulla Springshed has been conceptually divided it into three general areas based on the extent of confinement of the underlying Upper Floridan Aquifer or UFA (see map 2):

- **Streams Region (lotic or UFA confined)**
770 mi²; Groundwater recharge ~ 1 in/year
- **Lakes Region (lentic or UFA semi-confined)**
250 mi²; Groundwater recharge ~ 8 in/year
- **Karst Region (UFA porous unconfined)**
145 mi²; Groundwater recharge ~ 18 in/year

A list of the lakes and sinking streams included in this study is presented in table 1. The sinking streams are shown in map 3 and the sinking lakes in map 4. The Ochlockonee River, Lake Talquin, and the other lakes in Gadsden County were not included in this

study since they are perched on a very thick alluvial clay layer and do not seep into the aquifer. A more detailed description of the sinking lakes and streams is presented in Appendix I.

The NSILT includes four sinking streams: Lost Creek, Black Creek, Munson Slough, and Fisher Creek (Eller and Katz, 2014). Munson Slough should not be characterized as a sinking stream. In contrast, we treat Munson Slough as part of the Lake Munson sinking lake system. Lake Munson, which is formed by a dam on Munson Slough, receives approximately a third of the City of Tallahassee's storm water. The outflow from Lake Munson flows into a series of sinks in and around Ames Sink.

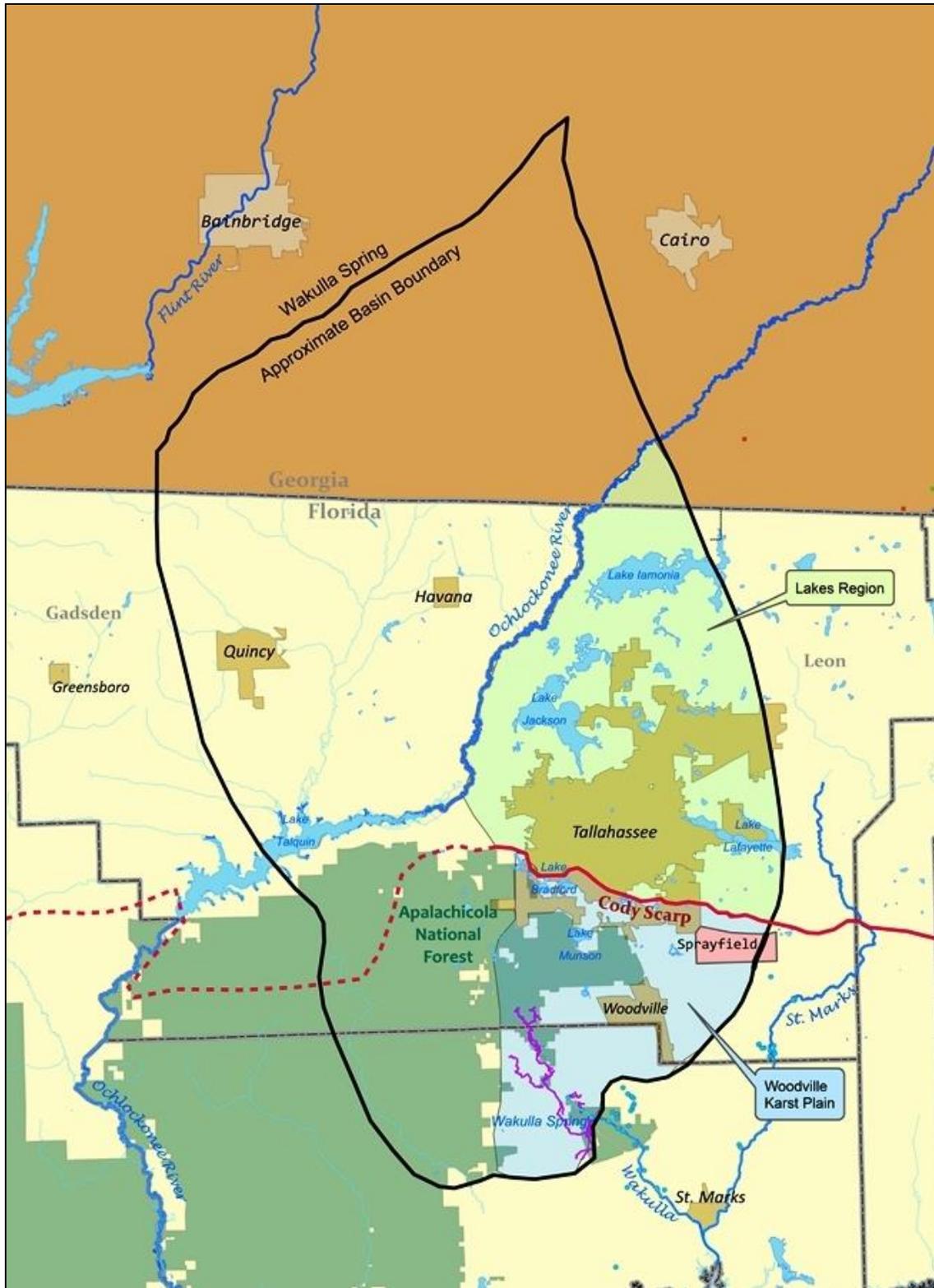
The vast majority of the water in the sinking lakes in the Wakulla Springshed is in the first five waterbodies: Iamonia, Munson, Miccosukee, Jackson, and Lafayette (see table 1). The other three are rather insignificant in the overall water budget of Wakulla Spring.

Ecologists divide continental waters into two categories: lentic and lotic. A lotic system has flowing waters. Examples include: creeks, streams, runs, rivers, springs, brooks and channels. A lentic system has still waters. Examples include: ponds, basin marshes, ditches, reservoirs, seeps, lakes, and vernal/ephemeral pools.

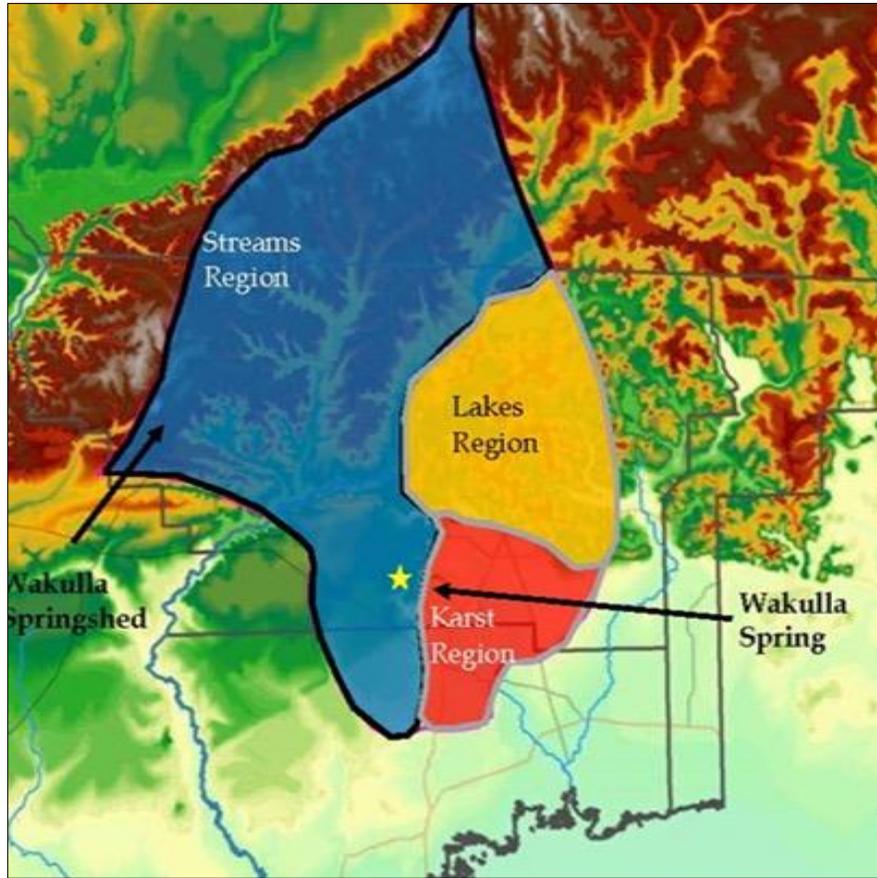
In karst areas sinkholes can form and capture the flow of surface streams. These sinking streams flow directly into caves or conduits within the aquifer through sinkholes called swallets. These are lotic systems. The water does not pond or spend any significant amount of time on the surface. The sinking stream water flows relatively freely and unimpeded into the aquifer, carrying its load of pollutants, derived from surficial runoff, directly into the aquifer (table 1; maps 2 and 3). In the Wakulla Springshed, because of the continuous flow and high current of the sinking streams, both particulate and dissolved contaminants flow directly into the UFA with little or no attenuation or degradation (Katz et al., 1997, 1998).

In karst areas where the aquifer is confined or semiconfined, surface water can be perched in a depression where the water collects and pools into temporary waterbodies, ephemeral ponds, or sinkhole lakes (table 1; maps 2 and 4). These are lentic systems, all periodically going dry, with varying hydroperiods. These waterbodies may have a surface water residence time of only a few weeks to several years. Most of the larger lakes in this study have residence times of several years. The increased residence time on the surface can have dramatic implications for water quality. Biological activity, particularly the metabolism and propagation of aquatic plants and algae, is coupled with increased nutrient loading from adjacent urbanization and development. These locations are considered desirable places to live, and tend to be over developed.

These lakes are natural sinkhole lakes. They are classified as the most critically endangered lake type in Florida by the Florida Natural Areas Inventory (FNAI, 2010) as specified in their *Guide to the Natural Communities of Florida*. Sinkholes usually swallow surface features, typically homes or roads. They suddenly appear, seemingly out



Map 1: A map of the Wakulla springshed (Barrios, 2014).



Map 2: The streams, lakes, and karst regions in the Wakulla springshed (FSI, 2014).

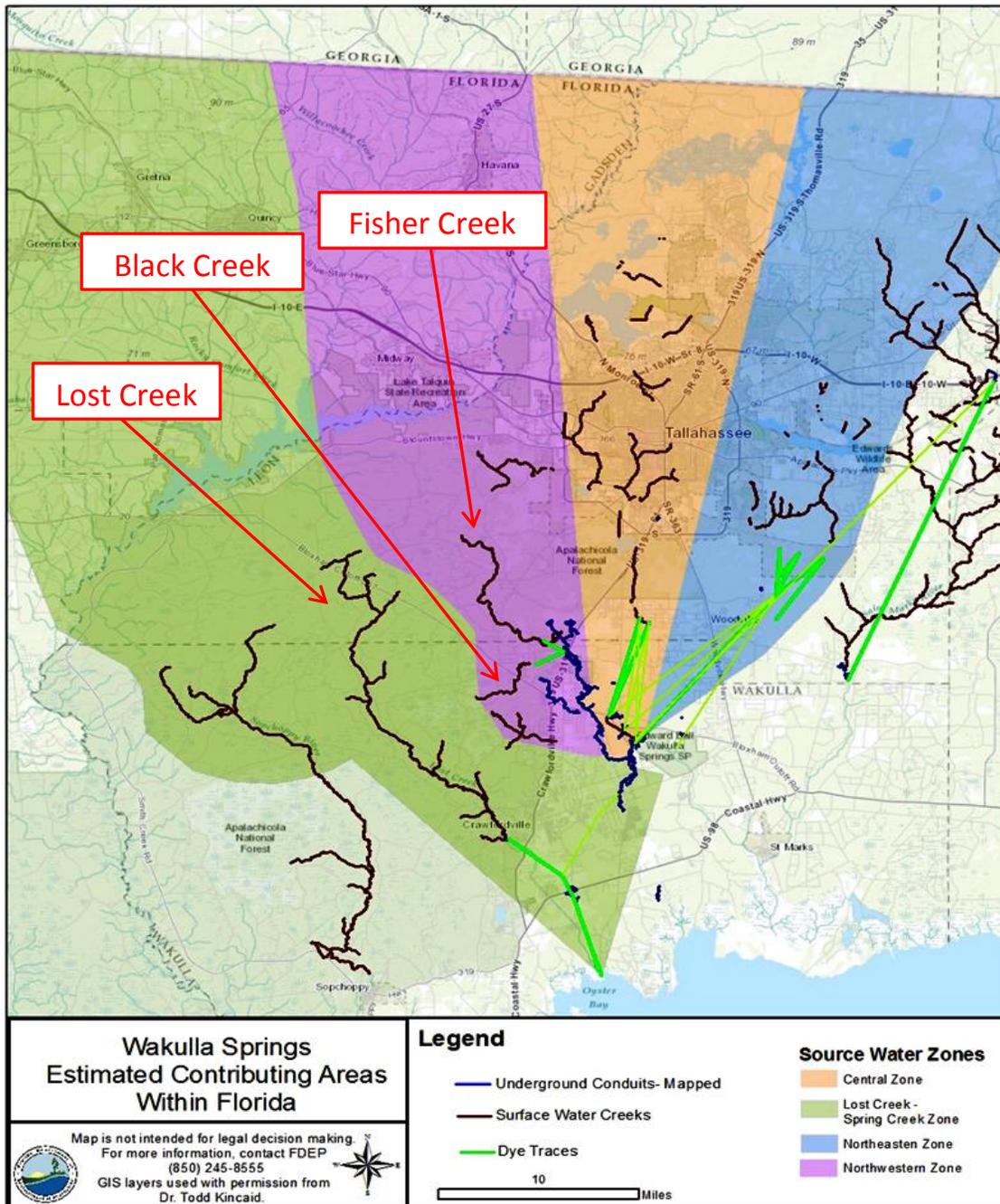
Table 1: Waterbodies included in this study.

Streams and Karst Regions: Lotic systems, listed by nitrogen loading capacity (map 3)

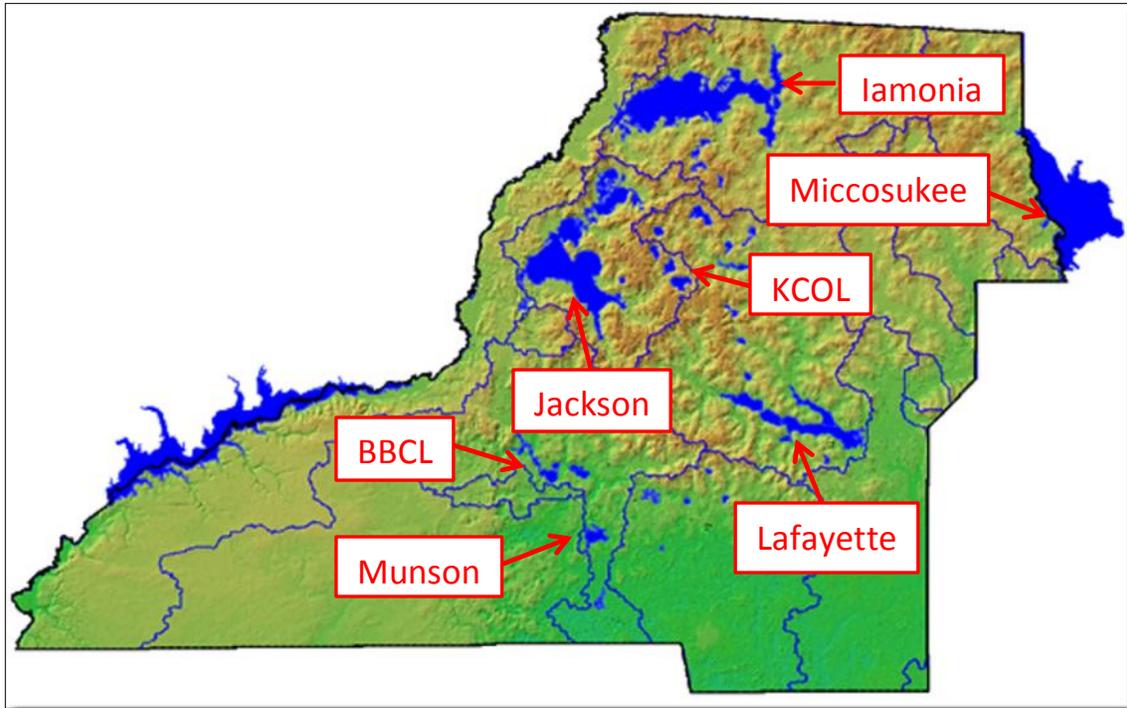
1. Lost Creek
2. Black Creek
3. Fisher Creek

Lakes Region: Lentic systems, listed by nitrogen loading recharge capacity (map 4)

1. Lake Iamonia
2. Lake Munson
3. Lake Miccosukee
4. Lake Jackson
5. Lake Lafayette (including its bermed compartments)
6. Bradford Brooks Chain of Lakes (BBCL)
7. Killlearn Chain of Lakes (KCOL)



Map 3: Streams included in this study (adapted from FDEP, 2015).



Map 4: Lakes included in this study (Mauldin, 2006).

of nowhere, only to be quickly filled in. A sinkhole lake is a more permanent feature, with a persistent depression caused by dissolution, or the continuous percolation of water, into underlying subterranean caverns in an aquifer which is connected to an underground river that flows through the porous lime rock to an outlet such as Wakulla Springs.

Therefore the water quality of the sinking streams and sinking lakes is very different, with the exception of specific conductance, a measure of the dissolved ions in the water, which is very low because they are both derived from rain water. Most of the sinking lakes in the Wakulla Springshed exhibit low color (color less than 40 platinum color units, as defined by the EPA methodology for color analysis) except for the Bradford Brooks Chain of Lakes which are fed with tannic water from the Apalachicola National Forest. Because of their long residence times, these lakes accumulate phosphorus and nitrogen from their urban drainage basins providing extremely productive habitats for all kinds of flora and fauna. These are fertilizers that tend to be assimilated by aquatic plants and algae and transformed into plant biomass. This is measured as chlorophyll, the green photosynthetic pigment in plants. In general, lakes with higher chlorophyll levels have higher nutrient levels.

Most of the sinking streams in the Wakulla Springshed flow through relatively undeveloped areas, including vast areas of the National Forest, and therefore also have good water quality. They are colored dark reddish brown with tannic acid from the leaf litter and organic matter that the water flows through on its journey to the aquifer, particularly from cypress trees in associated wetlands. The tannic flowing water of the

sinking streams, the associated high pH of the dark tannic acids, and low natural nutrient inputs inhibit biological productivity.

Data Sources

We calculated loading estimates for sinking streams and lakes in the basin based on additional flow, lake stage, and water quality data beyond that used in the 2014 NSILT study produced by FDEP (Eller and Katz, 2014).

Stream Flow Data

We obtained additional stream flow data from the United States Geological Survey (USGS) which improved and increased the flow monitoring sites by adding automated gauging at Black Creek in 2015 (table 2).

Table 2: Flow data sources for sinking streams.

Stream	Lost Creek	Fisher Creek	Black Creek
Station	USGS station 02327033	USGS station 02326993	USGS station 02326995
Location	At Arran	Near Hilliardville	Near Hilliardville
Start of Record	1998	2007	2015
End of Record	2016	2016	2016

Lake Stage, Precipitation, and Evaporation Data

Seepage rates are estimated from lake stage, precipitation, and evaporation. For the five major sinking lakes we used lake level (stage) data (table 3) and rainfall data (table 4) from Northwest Florida Water Management District (NFWMD) sampling stations. These multi-purpose automated weather stations allowed us to adjust the stage data with rainfall data from the same site.

Evaporation data was more difficult to obtain. We obtained monthly average pan evaporation (inches) measured using a four-foot diameter Class A evaporation pan at the University of Florida's Institute of Food and Agricultural Sciences Havana Agricultural Extension Office.

There was no automated stage data available for Lake Munson. We used data for the period 2002-2010 from the NSILT which the authors obtained from stage readings the NFWMD took on a gauge on Munson Slough downstream from Lake Munson and upstream from Ames Sink. This flow data is a conservative estimate of total discharge from the lake to the aquifer since it does not capture infiltration through the bottom of the lake. A new rating curve would have to be developed by the NFWMD to update this data.

There is also no stage data available for Lake Lafayette so we had to develop seepage estimates by other means. This lake can be divided into four somewhat discrete hydrological units: Upper Lake Lafayette (ULL); Piney Z; Lower Lake Lafayette (LLL), and Alford Arm. We estimated seepage for ULL from flow data for the Fallschase Sink modeled by Richard Weikowitz (Gilbert, 2012).

With a complete absence of data from LLL we assumed seepage rates similar to those of Lakes Iamonia and Miccosukee. All three are ‘prairie lakes’: long, shallow drain fields leading to a large open sinkhole. Both Iamonia (5757 acres) and Miccosukee (6312 acres) have control structures preventing the lake from draining into the sinkhole. LLL (1330 acres) is similar, physically, to the other lakes. It too is bermed off from its sinkhole in ULL. This is a conservative assumption regarding the LLL seepage flow to the aquifer. It is probably an underestimation because LLL is further south in the springshed than Iamonia or Miccosukee. It is near the Cody Scarp which separates the semiconfined and unconfined portions of the Wakulla Springshed. Thus LLL probably seeps at a greater rate than either Lakes Iamonia or Miccosukee.

Table 3: Stage data sources for sinking lakes.

Lake	Lake Jackson	Lake Iamonia	Lake Miccosukee
Station	NWF ID S649	NWF ID 12358	NWF ID 11355
Location	Millers Landing	Iamonia East	Outfall
Start of Record	2003	2012	2012
End of Record	2016	2016	2016

Table 3: continued.

Lake	Killearn Chain of Lakes	Lake Munson
Station	NWF ID 12549	NWF 11284
Location	Kanturk at Clifton	Munson Slough
Start of Record	2013	2002
End of Record	2016	2010

Table 4: Rainfall data sources for sinking lakes.

Lake	Lake Jackson	Lake Iamonia	Lake Miccosukee
Station	NWF ID S649	NWF ID 12358	NWF ID 11355
Location	Millers Landing	Iamonia East	Outfall
Start of Record	2012	2012	2012
End of Record	2016	2016	2016

Table 4: continued.

Lake	Killearn Chain of Lakes	Lake Munson
Station	NWF ID 12549	NWF 11284
Location	Kanturk at Clifton	Munson Slough
Start of Record	2013	2014
End of Record	2016	2016

Total Nitrogen Concentration Data

Total nitrogen includes nitrate, nitrite, ammonia, and organic nitrogen. To assess the nitrogen inputs attributed to these sinking waterbodies we collected total nitrogen concentration data for the three most recent years of National Laboratory Certification program (NELAC) water quality data from FDEP's STORage and RETrieval database (FLORIDA STORET). These include the following sources:

- Fisher Creek: Data generated by Leon County; 14 samplings from 2012-2015.
- Black Creek: Data from the 2008 final TMDL report for Black Creek (Wieckowicz et al., 2008).
- Lost Creek: Data generated by Leon County; 5 samplings from 2014-2015.
- Lake Munson (Ames Sink): Data generated by Leon County; 14 samplings from 2012-2015.
- Upper Lafayette (Fallschase Sink): Data generated by Leon County; 7 samplings, 2014-2015.
- Lower Lake Lafayette: Data generated by Leon County; 7 samplings, 2014-2015.
- Alford Arm: Data generated by Leon County; 7 samplings, 2014-2015.
- Piney Z: Data generated by the City of Tallahassee; 8 samplings, 2012-2014.
- Lake Jackson (Porter Sink): Data generated by Leon County; 11 samplings from 2012-2015.
- Lake Iamonia (Iamonia Sink): Data generated by Leon County; 10 samplings from 2012-2015.
- Killlearn Chain of Lakes: Data generated by McGlynn Labs; 30 samplings, 2013 to 2015.
- Lake Miccosukee: Data generated by Leon County; one sampling event available from 2012
- Bradford Brook Chain of Lakes: Data generated by Leon County; 15 samplings from 2012-2015.

Data Quality Assurance and Certification

We collected water quality data, including nitrogen concentrations, from all possible sources: the Florida Fish and Wildlife Commission, Northwest Florida Water Management District, City of Tallahassee, Leon County Public Works, Florida State University (FSU) Department of Earth, Ocean and Atmospheric Science, former FSU Center for Aquatic Research and Resource Management, Florida LAKEWATCH, and various homeowner associations. This data was loaded into a comprehensive data base. The data were graphed and some outliers were identified and rejected.

We also found and identified the most recent certified data from the National Laboratory Accreditation Program (NELAP) and the Florida Department of Health (FDOH) for all the waterbodies included in this study. All the lakes had certified data to the current

period, invariably quarterly monitoring, except for Lake Miccosukee where all data stopped being collected in 2012.

We decided to use the last two to four years of NELAP certified data, ending in 2015 for all water bodies except Lake Miccosukee, so that the loadings would be comparable and congruent with those used in the NSILT study. This data was obtained from the Florida STORET database which is maintained by FDEP to capture, store, and report chemical, physical, and biological water quality data for the TMDL program and for developing Basin Management Action Plans.

Gauging data was obtained either from the USGS or the NFWFMD and is not subject to Florida STORET data entry.

Methods for Estimating Total Nitrogen Loadings

Annual loadings of total nitrogen are calculated by multiplying annual median flows/seepage, adjusted for evaporation losses and precipitation gains, by the annual average total nitrogen concentration, adjusted for recharge rates based on the degree of confinement of the aquifer, and for attenuation of the nitrogen by the soils and geologic materials through which discharges from the sinking streams and lakes flow to the Upper Floridan Aquifer.

Precipitation Gains and Evaporation Losses

Precipitation gains to stream and lake water budgets are calculated from local rainfall data, most of which is available from the automated stage gauge rainfall meters. Evaporation pan water level readings are used to account for evaporation losses. We calculated evaporation losses by applying these rates to the surface areas of the lakes at their average annual elevations as reported by Florida Lakewatch (2016).

Recharge Factors, Attenuation Factors, and Seepage Rates

Recharge factors measure the percent of rainfall or other water discharge onto the land surface that infiltrates through overlying soils and geologic materials into an aquifer. We used the factor employed in the NSILT study for the unconfined aquifer, 90%, for both the sinking streams and the sinking lakes because both discharge directly into the UFA via sinkholes and/or seepage.

Attenuation factors measure the extent to which nutrient levels are reduced by physical, chemical, and biological processes that occur in the soils and geologic materials through which inflows to the aquifer infiltrate. The development of field-determined attenuation factors would require extensive water quality analysis of samples from wells around and under the waterbody, as well as laboratory testing of core samples. Therefore, this study

employs the attenuation factors used in the NSILT study which are based on research from karst areas as well as research on septic tank attenuation.

The three sinking streams enter the aquifer through open sinkholes. It seems logical that little or no natural attenuation of nutrients occurs in the sinking streams because they pour directly into the underwater caves of the aquifer. However, the NSILT study gives sinking streams an attenuation factor of 20% which we employ as well.

The sinking lakes are in solution basins where the water rapidly infiltrates into the aquifer primarily via seepage. The still, standing water seeps continually through their sediments where the confining layer can be quite leaky or even absent. All but one of the seven sinking lakes in this study, the Killlearn Chain, have active sinkholes, but seepage is the predominant inflow pathway into the aquifer. The NSILT study did not estimate seepage from sinking lakes and, therefore, does not include a separate attenuation factor for these sources. We used the 20% sinking stream attenuation factor as a best approximation.

Stage data from times of water level decline, where there was negligible precipitation, are most useful for determining seepage. Some continuous declining lake levels extended for years. This data was then adjusted for evaporation and precipitation. We compared results from different periods to assess accuracy.

Findings and Management Recommendations

This section presents the results of our analysis of total nitrogen loadings to the UFA from sinking waterbodies (streams and lakes) within the Wakulla Springshed and compares those findings with those of the NSILT study (Eller and Katz, 2014). Loadings for two components of total nitrogen (nitrate and ammonia), color, and chlorophyll a are reported in Appendix II.

Nitrogen loading from sinking waterbodies, with the addition of sinking lakes, increased from 2% to 6% of the input of total nitrogen to the land surface (figure 1). The sinking waterbodies rise to second place in the loading chart after attenuation and recharge factors are applied (figure 2). The sinking waterbodies rise in total nitrogen loading to the UFA from 10% to 17% making these karst waterbodies the second largest source of nitrogen loading within the Wakulla Springshed after septic tanks.

Flows for the sinking streams were underestimated in the NSILT study and there was no estimation of loading from the sinking lakes, except for Lake Munson which was classified as a sinking stream (via Ames Sink). Since the writing of the NSILT study, the USGS has upgraded and enhanced its flow monitoring sites, including the new USGS gauging site at Black Creek (2014). The NFWFMD installed hydrological stations with metered stage, rainfall, flow, and other water quality data on most other waterbodies in the Springshed. These include new gauging stations on Lakes Jackson (2012), Iamonia (2012), and Miccosukee (2012) and the KCOL (2013). This new data allowed the calculation of seepage rates for the first time for seven sinking lake systems: Lafayette

(assorted compartments), Miccosukee, Iamonia, Jackson, Bradford Brook Chain of Lakes (BBCL), and KCOL. Following the practice in the NSILT study, we used annual median flows for the sinking streams to dampen the effects of extreme outlier events, but we used annual average seepage rates for the lakes. Annual flows/seepage rates for all of the sinking waterbodies are presented in figure 3.

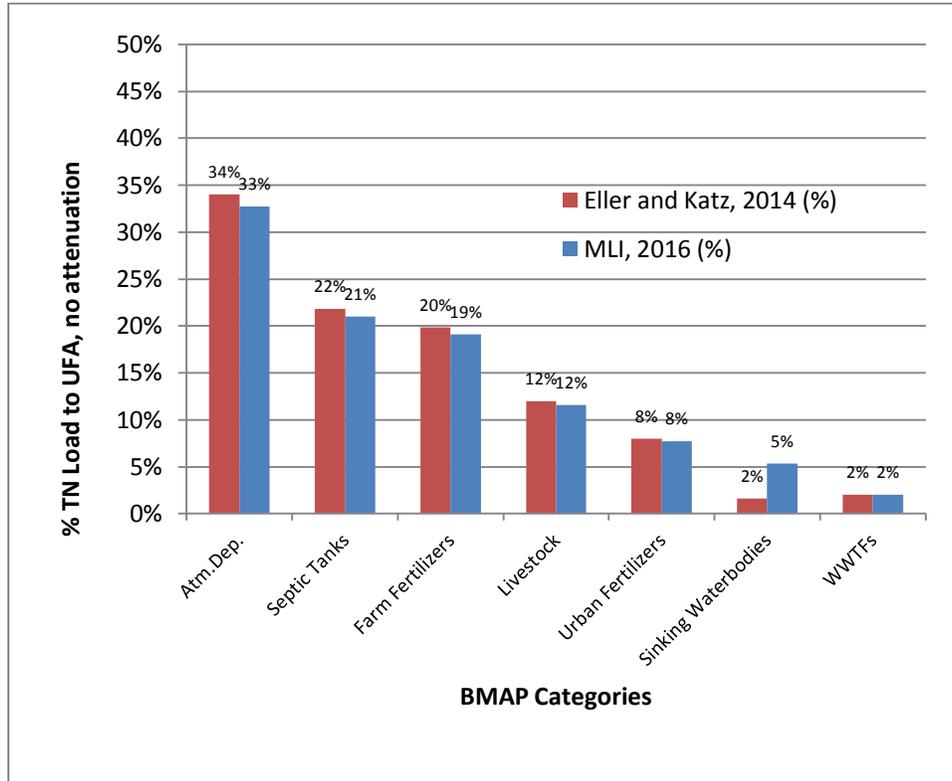


Figure 1: Comparison of total nitrogen loadings to the land surface without attenuation or recharge over the Upper Floridan Aquifer within the Wakulla Spring and River BMAP area by source category for the NSILT study (Eller and Katz, 2014) and this study (MLI, 2016).

The annual flows (figure 3) were multiplied by the annual total nitrogen concentrations (table 5) and adjusted with recharge factors and attenuation factors from the NSILT to yield the average annual loadings from these waterbodies to the Upper Floridan Aquifer (table 6). Relying on more recent water quality data for the three sinking streams, we document higher annual average total nitrogen concentrations than those reported in the NSILT study for Lost Creek (0.73 vs. 0.66 mg/L) and Fisher Creek (0.76 vs. 0.63 mg/L). Our annual average concentration is lower, however, for Black Creek: 0.70 vs. 1.07 mg/L.

Figure 4 depicts the annual average percent loadings of total nitrogen to the UFA by sinking waterbodies from individual sinking streams and sinking lakes in the Wakulla Springshed. These graphics demonstrate the high relative importance of Lost Creek, which contributes one third of all total nitrogen loadings from sinking waterbodies in the

Wakulla Springshed. Note also that Lake Iamonia, which lies furthest north of all the sinking waterbodies, is the second most important source of total nitrogen, followed by Fisher Creek, Lake Lafayette (all sections) and Lakes Miccosukee, Jackson, and Munson.

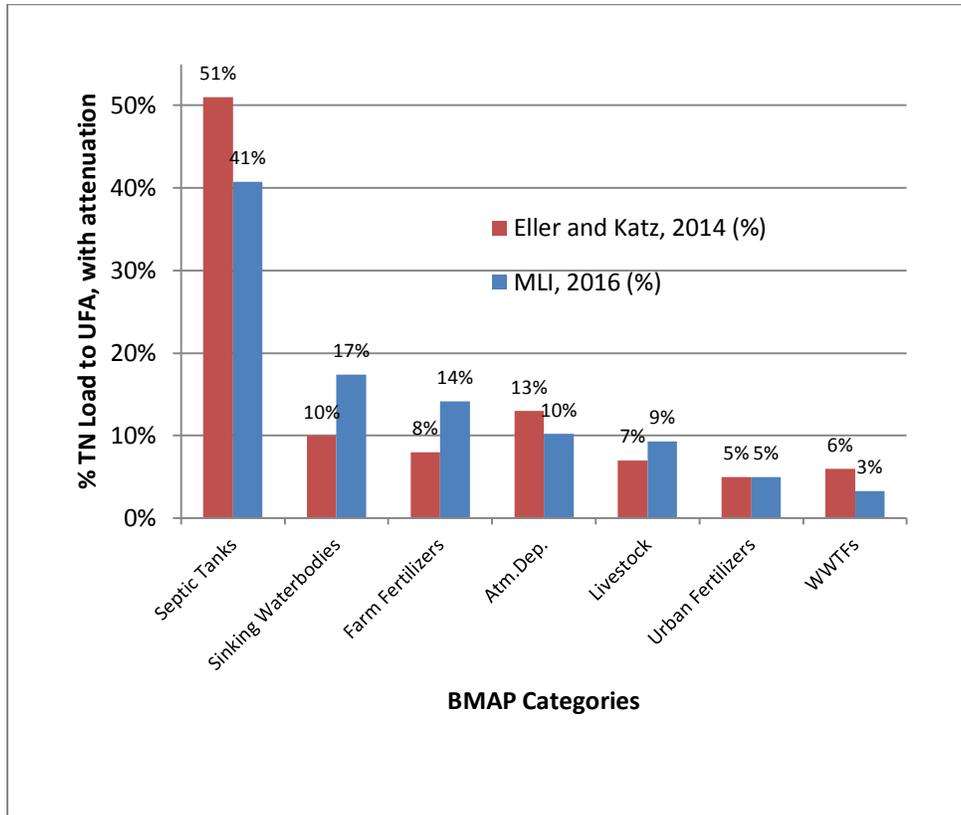


Figure 2: Comparison of relative estimated total nitrogen loadings to the Upper Floridan Aquifer within the Wakulla Spring and River BMAP area after the application of attenuation and recharge factors by source category for the NSILT study (Eller and Katz, (2014) and this study (MLI, 2016).

Table 7 compares annual flows, annual average total nitrogen concentrations, total nitrogen loadings, and total percent nitrogen loadings for sinking streams and sinking lakes. The flow data demonstrate that there is somewhat similar recharge of water to the aquifer from the sinking streams and the sinking lakes. The loadings of total nitrogen are similar too (see figure 5). This reflects higher annual average total nitrogen concentrations in the sinking lakes, with substantially higher concentrations in two of the lakes that receive urban storm water from the City of Tallahassee: Lakes Lafayette and Munson (see table 5).

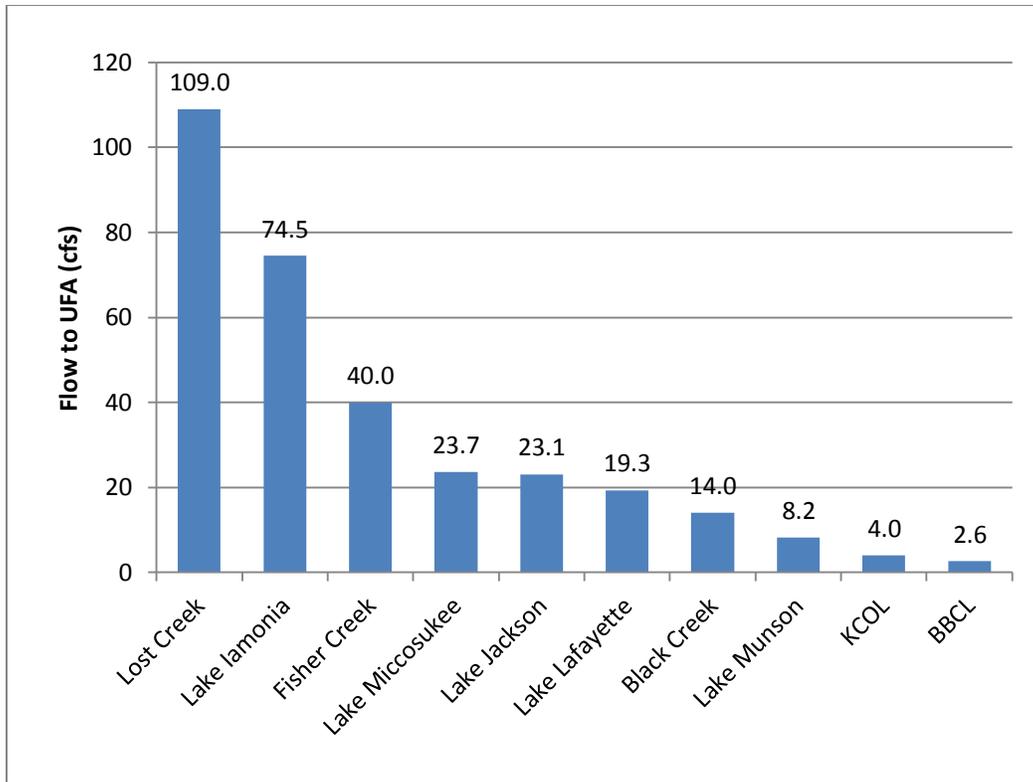


Figure 3: Annual median flows of sinking streams and annual average seepage flows of sinking lakes in the Wakulla Springshed listed in declining order.

Table 5: Annual average total nitrogen concentrations of individual sinking waterbodies adjusted for attenuation and recharge.

Sinking Waterbody	Total Nitrogen Concentration (mg/L)	Years of Flow Data
Lake Munson	1.573	2002-2010
Lake Lafayette	1.041	2016
Lake Miccosukee	0.825	2012-2016
Fisher Creek	0.755	2007-2016
Lost Creek	0.730	2014-2016
Black Creek	0.700	2015 -2016
BBCL	0.697	2005-2006
Lake Iamonia	0.687	2012-2016
Lake Jackson	0.652	2002-2016
KCOL	0.607	2003-2016

Table 6: Annual average loadings of total nitrogen to the Upper Floridan Aquifer from individual sinking waterbodies in the Wakulla Springshed.

Sinking Waterbody	Total Nitrogen Loading (kg-N/yr)
Lost Creek	51,146
Lake Iamonia	32,908
Fisher Creek	19,410
Lake Lafayette	12,923
Lake Miccosukee	12,571
Lake Jackson	9,685
Lake Munson	8,293
Black Creek	6,301
KCOL	1,561
BBCL	1,165

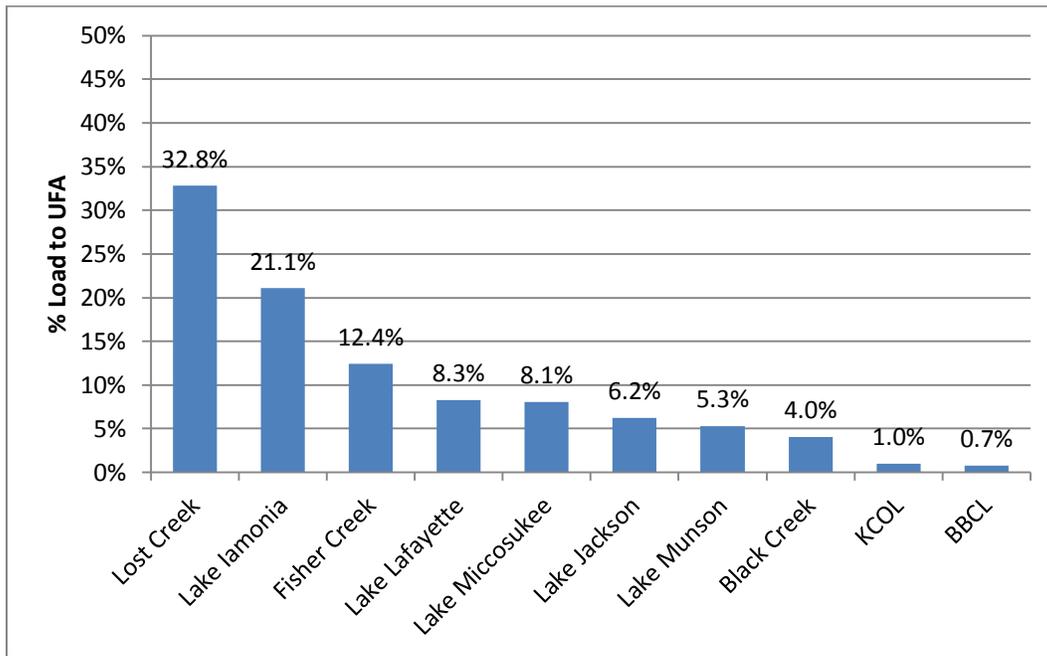


Figure 4: Annual percent loadings of total nitrogen from individual sinking streams and sinking lakes in the Wakulla Springshed.

Table 7: Comparison of annual average flows, total nitrogen concentrations, and loadings for sinking streams and sinking lakes.

Sinking Waterbody	Annual Flow (cfs)	Annual Average Total Nitrogen Concentration (mg/L)	Total Nitrogen Loading (kg/yr)	Total Nitrogen Percent Loading
Sinking Streams	163	0.728	76,857	49%
Sinking Lakes	155	0.869	79,106	51%

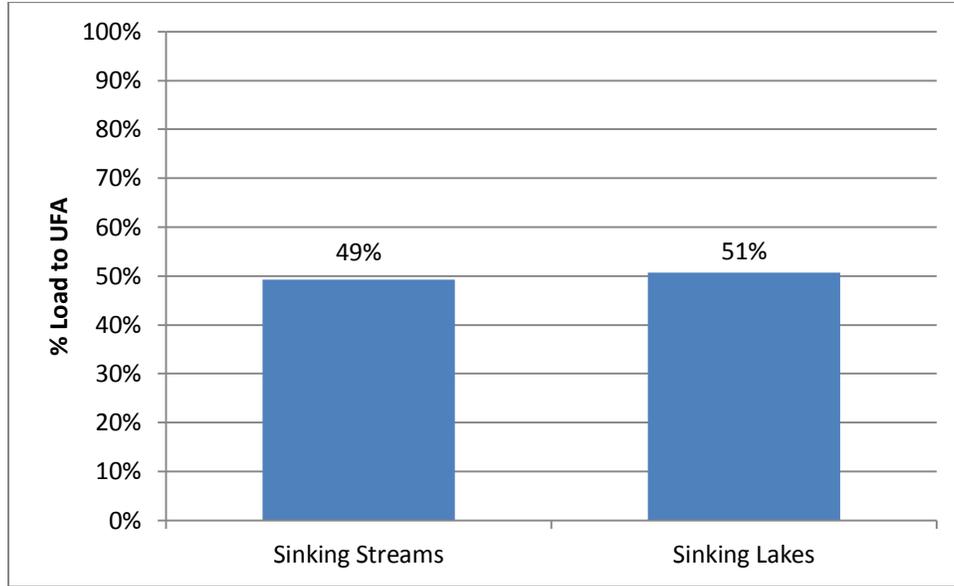


Figure 5: Annual percent loadings of total nitrogen from sinking streams and sinking lakes in the Wakulla Springshed.

Management Recommendations

Our findings offer new insights to inform efforts to remediate the impaired biological condition of Wakulla Spring and the Upper Wakulla River through the Basin Management Action Plan (BMAP) for the system. Taking account of the total nitrogen loadings contributed by sinking lakes, in addition to those from sinking streams, increases the total nitrogen loading estimate for sinking streams and lakes to the Upper Floridan Aquifer in the Wakulla Springshed from 10% to 17% (figure 2) making these sinking waterbodies the second largest source of nitrogen loading that can be remediated in the Wakulla Springshed after septic tanks. We recommend, therefore, that FDEP reflect these findings in the next revision of the Wakulla Spring and Upper Wakulla River BMAP and that they target sinking waterbodies in implementing the next phase of the BMAP.

Our analyses also reveal that the three largest sources, which comprise 66% of the annual loadings of total nitrogen, are waterbodies which receive little direct discharge of nitrogen from human sources. Lost Creek (32.8%) and Fisher Creek (12.4%)

predominantly drain forest land. Lake Iamonia (21.1%) receives some of its nutrients from flooding of the nutrient rich, Ochlocknee River, which flows from Georgia (McGlynn, 2000). These findings suggest that remediating the sinking waterbodies, at 17%, the most significant nitrogen loading source to the UFA after the remediation of septic tank loadings, should be a priority in the next revision of the Basin Management Action Plan for restoring water quality in the Upper Wakulla River and Wakulla Springs Basin.

These findings suggest that remediating urban storm water loadings to the large urban lakes, i.e. Jackson, Lafayette, and Munson, which contribute 20% of the total nitrogen loadings from the sinking waterbodies, should be a remediation priority in the next revision of the Basin Management Action Plan for restoring water quality in the Upper Wakulla River and Wakulla Springs Basin

Recommendations for Further Research

We recommend the following initiatives to improve the accuracy of nitrogen loading estimates to the Upper Floridan Aquifer (UFA) from sinking water bodies within the Wakulla Springs and Upper Wakulla River basin.

- 1) Initiate additional automated water level (stage) monitoring to enable improved seepage rate calculations for Lake Miccosukee, Upper Lake Lafayette, Lower Lake Lafayette, Alford Arm, Lake Piney Z, Lake Munson, and Ames Sink.
 - a. These waterbodies are connected to the aquifer and load pollutants to it, but there is no automated continuous monitoring of water level (stage data) for any of them. Automated water level gauges maintained by the NFWMD at these locations would enable more accurate estimates of nitrogen loadings to the UFA.
 - b. Neither Lake Lafayette nor Lake Munson has any water level metering so the seepage rates cannot currently be accurately determined. We made rough, deliberately conservative estimates using limited available data.
 - i. Lake Lafayette is divided into four different hydrological units (Upper Lake Lafayette, Lower Lake Lafayette, Alford Arm, Lake Piney Z). We estimated discharge from Upper Lake Lafayette based on flow data from Fallschase Sink. We assumed seepage from the other three units is similar to that determined for Lakes Iamonia and Miccosukee. All four need water level metering to produce more accurate estimates. While the staff gauge in the Fallschase Sinkhole is useful, physical observations at the site do not satisfy the need for continuous automated stage monitoring.
 - ii. Lake Munson has no water level metering either and there are no flow measurements at Ames Sink. We used the NSILT study estimates for flow at Ames Sink, which were produced from manual stage readings on the slough and a rating curve. We have assigned nitrogen loading to Lake Munson based only on those flow estimates. This probably underestimates the Lake Munson

loading, because it is a large shallow karst lake located in the Munson Sand Hill Ecoregion where there is very little confinement of the aquifer., On the other hand, the lake bottom may be effectively sealed with silt and detritus from the City of Tallahassee storm water and sewage inputs it has received over the decades. Considering that the NSILT study flow medians were much lower than flow medians from more recent continuous monitoring stations now on the creeks, it is probable that the Munson flow estimates in the NSILT study are approximately half of the actual flow. The flows of the sinking streams were also considerably higher than the flows in the NSILT study.

- 2) Develop separate estimates for sinkhole discharges and for seepage through lake bottom sediments, particularly for the lakes in the semi-confined lakes region where clay bottom sediments impede seepage.
 - a. Lake discharge estimates based solely on lake stage reflect both bottom seepage and discharge through active sinks in lake bottoms. In the semi-confined lakes region (Lakes Iamonia, Jackson, and Miccosukee, and the Killlearn Chain of Lakes), the clay soils are likely to attenuate total nitrogen to a greater extent than occurs via direct discharge through lake sinks. Separate estimates for discharges through bottom seepage and lake sinks would provide more accurate estimates of nitrogen loadings from such lakes. Where lakes are situated over sandy soils in the unconfined region (Lakes Lafayette and Munson and the Bradford Brook Chain of Lakes), very little nitrogen attenuation is likely for discharges via bottom seepage, so combined discharge estimates based on lake stage should suffice.
 - b. Lake sinkhole flows can be measured directly with flow meters when lakes are full or sink discharges can be estimated from flows into the sinks when lakes are dry. Seepage can be measured with seepage meters, and in some cases shallow wells along the edges of lakes.
 - c. The major flows into sinkholes should be monitored directly for flows and pollutant concentrations, during and between events. The flows into Ames Sink from Munson Slough do not have continuous monitoring and several of the flows into the Fallschase Sink have no monitoring either, like the flow from the new Weems Pond alum pollution reduction facility
- 3) Develop more refined attenuation factors for sinking lakes and sinking streams.
 - a. The NSILT study does not address sinking lakes and therefore provides no total nitrogen attenuation factor for those waterbodies, most of which discharge to the UFA through both active sinkholes and bottom seepage. In this study we assigned to the lakes, the same rather conservative attenuation factor of 20% used in the NSILT study for sinking streams. This could be revised with further research. As noted above, different attenuation factors should be defined for these two discharge modes for the lakes within the semi-confined lakes region and those factors applied to those discharge rates to estimate nitrogen loadings.

- i. Properly placed seepage meters, lysimeters or shallow monitoring wells, positioned so we can compare total nitrogen levels in the seepage from the lake with the surrounding groundwater, could serve to verify the seepage (recharge/attenuation).
 - b. The attenuation factor of 20% assigned in the NSILT study for sinking streams needs to be re-evaluated.
 - i. Some water may enter the aquifer via seepage through the stream bottoms, but the majority of the flow descends through sinkholes, which are open windows into the aquifer, at an average speed of 1 cfs.
 - ii. It seems unlikely that any remediation of total nitrogen occurs at all, thus the attenuation factor for sinkholes is more likely close to 0%. Automobiles, people and pets have been observed to be consumed in this flow and transported into the aquifer, emerging from the aquifer, downstream in a spring, so how could a molecule be removed?
 - iii. Monitoring of pollutants and flows before and after weather events that initiate sinking stream/lake flows into sinkholes at karst features, like Lost Creek, Fisher Creek, the Fallschase Sink, Lake Miccosukee, and Lake Munson, in association with monitoring wells in the flow paths, could be used to better estimate total nitrogen attenuation, for both sinkholes and seepage. These areas are currently inadequately monitored.
 - c. The attenuation factors vary for each water quality parameter and can be variable even for the same parameter under different environmental conditions. While not within the scope of this project, attenuation factors are needed for other contaminants that affect spring water quality such as petroleum hydrocarbons, total phosphorus, color and chlorophyll, as well as common pesticides and herbicides, surfactants and pharmaceuticals.
- 4) Initiate regular water quality monitoring of Lake Miccosukee.
 - a. Total nitrogen data for only a single recent year (2012) are available in the STORET data base for Lake Miccosukee. Leon County formerly monitored water quality in the portion of the lake within the county but has discontinued doing so. Jefferson County, in which the majority of the lake is located, has never monitored water quality. Given the potentially large flow from this lake to the UFA (ranked fourth in figure 3), we recommend that the Northwest Florida Water Management District pick up the slack.
 - b. Water quality monitoring for a standard suit of parameters, not just nitrogen, should be increased from quarterly to monthly in all of the major sinking waterbodies in the Wakulla springshed.
 - i. Quarterly data is the minimum monitoring frequency required to account for seasonality. While quarterly data is considered statistically significant and acceptable for the TMDL program, monthly data covers more variability and events and gives a better picture of the health of the waterbody.

- ii. At a minimum, waterbodies facing water quality stress should get monthly monitoring, i.e. Lake Jackson, Upper Lake Lafayette, and Lake Munson. Doing so will enhance our estimates of total nitrogen loadings from these waterbodies to the UFA.

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Appendix I: Descriptions of Sinking Waterbodies

Lost Creek, Black Creek, and Fisher Creek are sinking streams; all have large active swallets where their waters flow into the ground, disappearing from the surface and entering the aquifer. Lakes Iamonia, Munson, Miccosukee, and Jackson, portions of Lake Lafayette, as well as the Bradford Brooks Chain of Lakes all contain active open sinkholes which periodically drain all or most of the water from these lakes into the aquifer. The Killlearn Chain of Lakes has had active sinkholes in the past, but none are currently functional.

Lost Creek has most of the flow and dominates the flows of waterbodies in the Wakulla Springshed. The sum of the median flows from the next four lakes, Iamonia, Miccosukee, Jackson and Lafayette, exceeds the flow of Lost Creek. These are the larger lakes in the Springshed, and even though they have slower seepage rates than the lakes farther south, they hold more water and thus have greater total seepage than the fast seeping more southerly lakes - the Bradford Brooks Chain of Lakes and Lake Munson (figure I-1). Those smaller lakes in the south have the greatest flows per unit area in the Springshed (figure I-2), but the lack of confining layers limits their size and they become insignificant compared to the larger lakes up north and the sinking streams down south in the Springshed. These smaller lakes in the south of the Springshed may represent a transition from the large sinkhole lakes in the north, where the semi-permeable clay layer holds more water and the sinking streams of the south where there are no significant confining layers and the water pours unimpeded into the aquifer, without ever becoming a permanent lake.

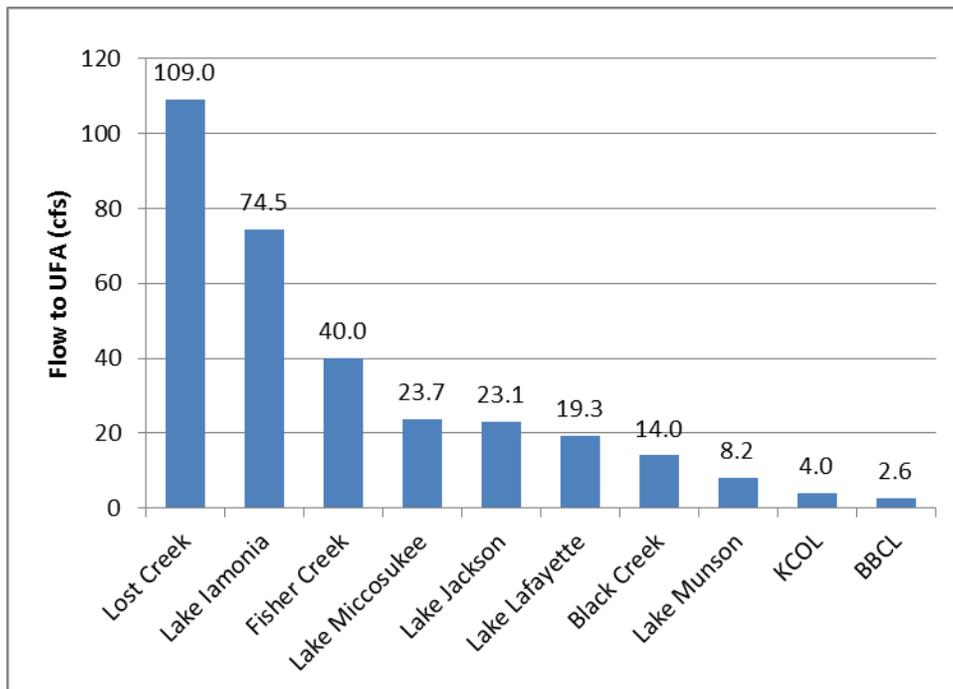


Figure I-1: Annual median flow per waterbody.

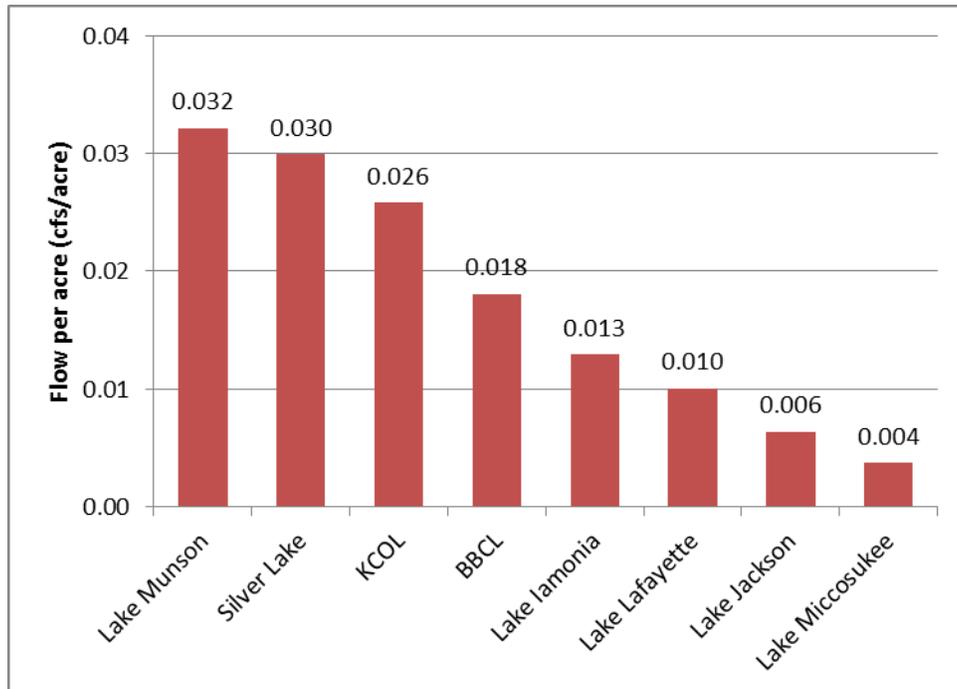


Figure I-2: Annual median flow per acre.

Sinking Streams (Lotic Systems)

Black Creek, Fisher Creek, and Lost Creek all originate in the Apalachicola Coastal Lowland and disappear into sinkholes that flow into the UFA (figures I-3, I-4, and I-5). Their annual median flows are often less than 10 cfs but they can have considerable flow for extended wet periods (Lost Creek 1998-2016; Fisher Creek 2007-2016; Black Creek 2015-2016). All these creeks can be considered flashy with flows varying greatly from time to time (figure I-6). There are few creeks in the Karst Region of the Wakulla Springshed due to the thin, highly permeable soils overlaying the UFA, allowing direct recharge to the UFA (map 2).



Figure I-3: Lost Creek swallet (2014, Cal Jamison).



Figure I-4: Fisher Creek swallet (2015, Seán McGlynn).



Figure I-5: Black Creek swallet (2015, Seán McGlynn).

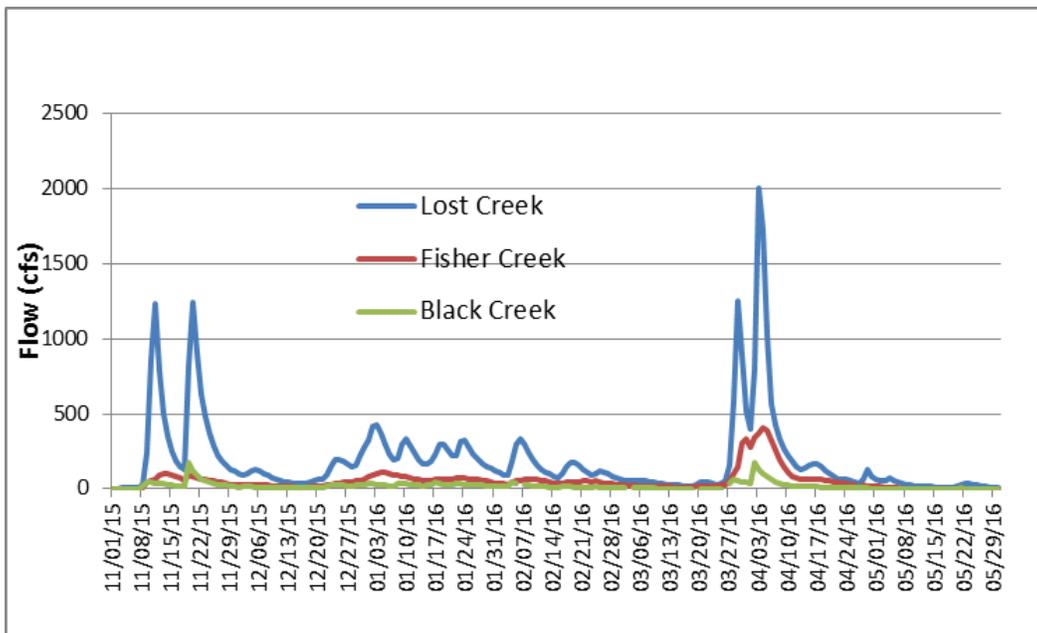


Figure I-6: Stream flow in Lost, Fisher, and Black Creeks (11/01/15-05/30/16).

Lost Creek and Fisher Creek

- Flow to the UFA via swallets
- Good water quality

Lost and Fisher Creek's flows originate in the Apalachicola Coastal Lowlands, and flow into the Karst Region where Lost Creek drains entirely into the UFA at the Lost Creek swallet and Fisher Creek drains into the UFA at a swallet. The majority of flow from the sinking streams that discharge to the UFA within the Wakulla Springshed is from Lost Creek. The annual median flow of Lost Creek is 109 cfs and that of Fisher Creek is 40 cfs, but the Lost Creek flows can be over 4000 cfs after a heavy rain.

Black Creek

- Flows to the UFA via swallet
- A final TMDL has been issued on Black Creek for fecal coliform (Wieckowicz et al., 2008)
- Impaired water classification for dissolved oxygen (FDEP, 2016a)

Black Creek's flow also originates in the Apalachicola Coastal Lowlands. It flows into the Karst Region where it also drains into the UFA at the Black Creek swallet. Black Creeks flow is less than Lost and Fisher Creek. The annual median flow is 14 cfs.

Sinking Lakes (Lentic Systems)

Lake Iamonia

- Poor water quality (McGlynn, 2000)
- Contains sinkholes and seepage areas which discharge water to the UFA
- Goes dry during droughts

Lake Iamonia occupies 5757 acres (at 98.6 ft NGVD) in Leon County, 12 miles north of Tallahassee and 2.5 miles south of the Georgia border. Its drainage basin comprises 101 square miles. The lake is seven miles long and two miles wide. It is a shallow subtropical lake, with an average depth of less than 5 feet.

Water historically flowed into the western end of Lake Iamonia from the Ochlockonee River through a series of sloughs and drained to a sinkhole at the eastern side of the lake. Iamonia has the second highest loading of TN to the UFA per table 6 in the main text, almost twice as much as Lake Lafayette which ranks third. Lake Iamonia can fill completely with water from the Ochlockonee in only a few days; this has happened multiple times a year. The nutrients in the Ochlockonee River are very high (McGlynn, 2000).

Near the sink there is a karst valley that contains 32 different places where water drains into the aquifer. Thus the volume of water in Lake Iamonia is primarily impacted by water from the Ochlockonee River (which is impacted by rainfall in Southwestern Georgia) and less so by water in its own drainage basin.

Lake Munson

- TMDLs for dissolved oxygen, nutrients, and turbidity (Gilbert et al., 2013).
- Contain sinkholes and seepage areas which seep water to the UFA
- Goes dry during droughts

Lake Munson, with a surface area of 255 acres, drains into a large active sinkhole, Ames Sink, via Munson Slough. There are 32 different places around Ames Sink where water drains into the aquifer. This lake has a 44,360 acre drainage basin and receives over a third of the City of Tallahassee's urban storm water. Lake Munson was historically the sewage outfall for the City of Tallahassee until 1984. Nutrient loading from urban storm water is still a problem in Lake Munson. FDEP has issued final TMDLs for dissolved oxygen, nutrients (trophic state index), and turbidity for the lake, as well as TMDLs for dissolved oxygen and un-ionized ammonia for Munson Slough downstream of the lake (Gilbert et al., 2013). Recent dye studies have shown that Ames Sink, the sinkhole drain for Lake Munson, is hydrologically connected to the Wakulla Springs (Dyer, 2015).

In 1950 a permanent dam was built at the outfall of the lake. From 1934 to 1984, Munson Slough was the receiving water body for Tallahassee's municipal waste water discharges (City of Tallahassee, 2012). The construction of the Southeast Farm Wastewater Reuse Facility in 1984, replaced the effluent discharge to Munson Slough.

A thick layer of organic muck coats its bottom. In 2000, Leon County was the recipient of \$13.3 million for restoration projects for Lake Munson. An additional six million dollars were used to complete removal of sediments from the northern portion of the lake bottom after Tropical Storm Allison flushed sediment through the basin in 2001.

Lake Munson has a history of frequent fish kills, infestation with invasive exotic plants, including *Hydrilla verticillata*, and animals. In late 2005 invasive exotic Channeled Apple Snails (*Pomacea canaliculata*) appeared in the lake and the aquatic macrophytes, including exotics, disappeared within a year. Lake Munson has since lacked any higher plant growth, except the mighty cypress trees which continue to ring its shoreline. The lake has had a persistent algal bloom since September 2005. This algal bloom is composed of *Microcystis*, a species of cyanobacteria (commonly referred to as bluegreen algae that are known to produce toxins called cyanotoxins).

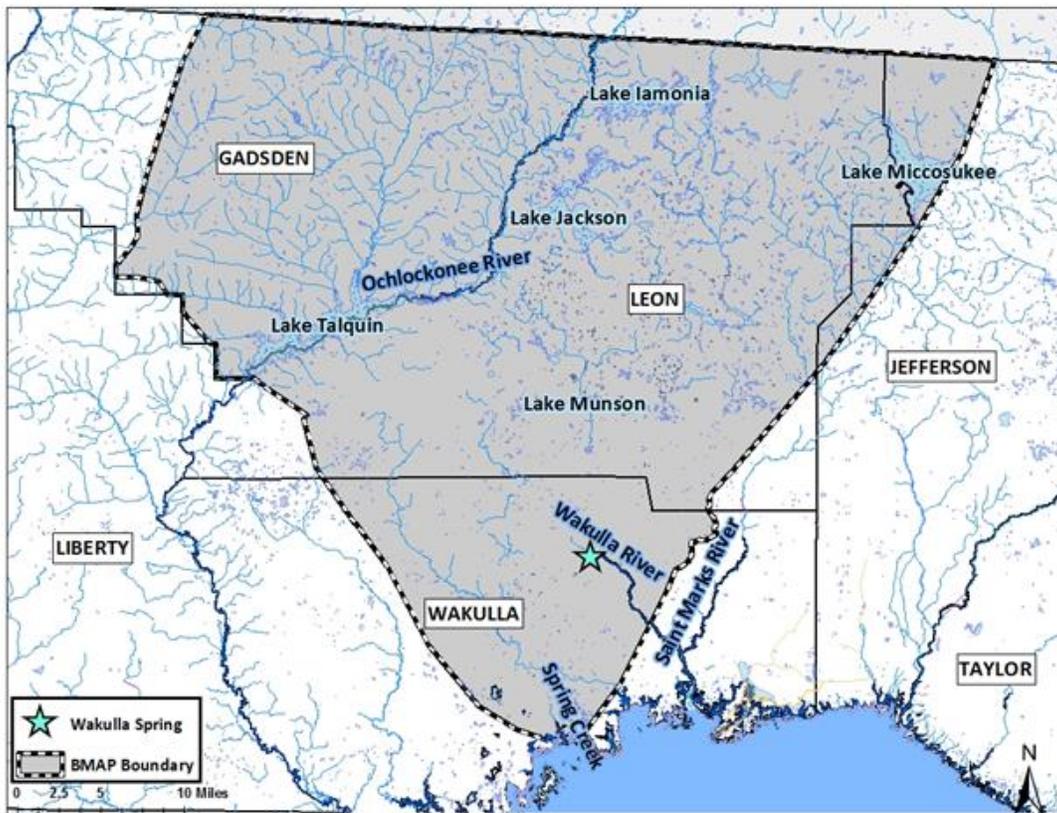
Lake Miccosukee

- Outlet stream classified as impaired for fecal coliform (FDEP, 2016a).
- Contain sinkholes and seepage areas which discharge water to the UFA
- Goes dry during droughts

With a surface area of 6,312 acres, Lake Miccosukee lies predominantly in Jefferson County along its western boundary with and within Leon County. The drainage basin encompasses over 25,000 acres in Leon County and a lot more acreage in Georgia and Jefferson Counties. It appears to be within the Wakulla Springshed, but its waters may

flow to the St. Marks basin at least some of the time. Lake Miccosukee was not included in the Wakulla Springshed map prepared by Barrios (2014), but it is included in the springshed basin of the final BMAP (FDEP, 2015) (map I-1).

A dye trace study is needed to clarify its hydrological situation (McGlynn et al., 2006). This large karst lake has large open sinkholes at both ends (figure I-7). Aquatic plant cover has historically varied on Lake Miccosukee due to fluctuating water levels. This lake used to drain and fill on what appears to have been a 10-year cycle. Descriptions of Lake Miccosukee have varied over time, particularly in regard to coverage of the lake's surface with aquatic plants. Current aerial photographs show a plant-clogged lake, with only 19% of the lake's surface area considered open water.



Map I-1: Wakulla Spring and Upper Wakulla River BMAP area including Lake Miccosukee (FDEP, 2015).

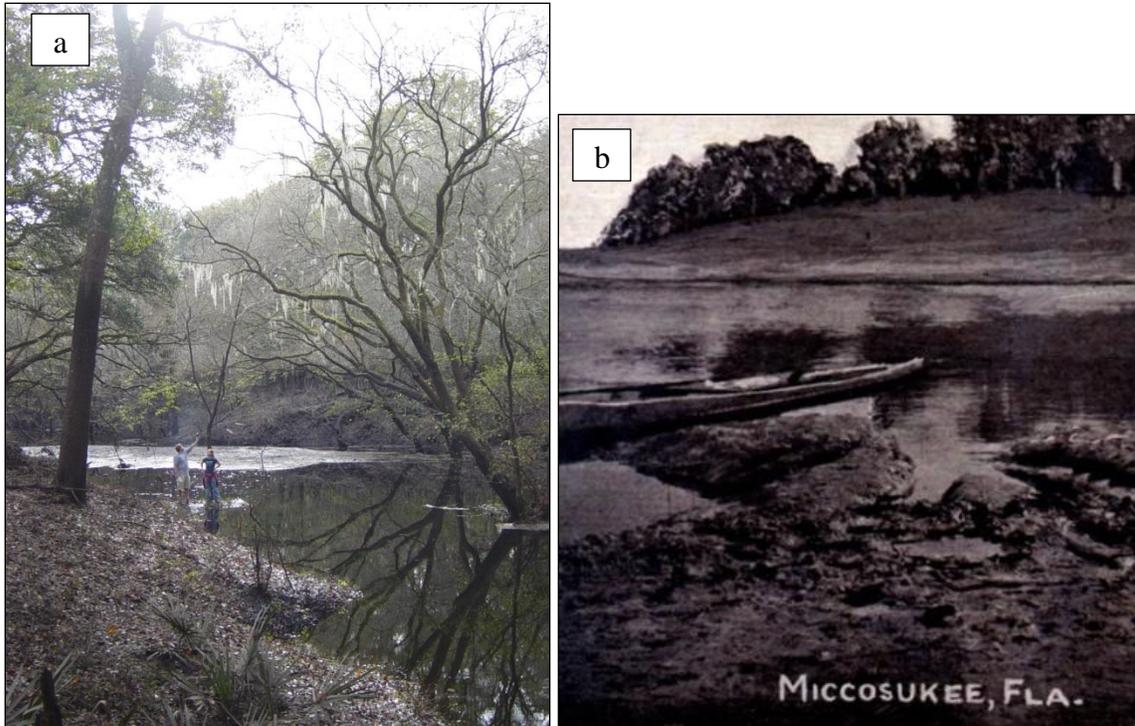


Figure I-7: (a) Sinkhole on southern side of Lake Miccosukee (Seán McGlynn, 2004); (b) postcard of sinkhole other side of the lake (Florida Memory, 1912).

Lake Jackson

- Classified as impaired for dissolved oxygen and nutrients (FDEP, 2016a)
- Contains sinkholes and seepage areas which discharge water to the UFA
- Dries during droughts

With a surface area of 4,001 acres and a drainage basin of 26,000 acres, Lake Jackson is one of the best examples of a disappearing lake in the world. Lake Jackson is an Outstanding Florida Water body and the only fresh water lake in Florida designated as an Aquatic Preserve by FDEP. However, FDEP (2016) has classified the lake as having impaired water quality for dissolved oxygen and nutrients based on trophic state index.

Water levels in the lake vary dramatically with the lake draining entirely from time to time through several sinks. After the drought of 1956, Lake Jackson was dry for a number of years. Local residents were frustrated by the empty lake and the major sinkholes in Lake Jackson (Lime, Porter Hole and Meginnis), so all the sinkholes became filled with crushed automobiles and cement. Water levels were stabilized and property values as well as fishing time were maximized. Flooding followed this dry event, possibly because none of the sinkholes were drawing water. Porter Hole Sink drained Lake Jackson in 1983 for a short time, while Lime Sink remained sealed until May 7, 2000, and then only opened slightly. Meginnis Sink has still not reopened.

Exploration of the caverns under Lake Jackson began with Tom Scott from the Florida Geological Survey after the natural drawdown in 1999. Beneath the dry lake, and extending to the northwest and the southeast, spelunkers explored and mapped caves at a depth of about 50 feet below the former bottom of the Lake. Since Lake Jackson is about 105 feet above sea level, this submerged passage represents the potentiometric surface of the aquifer, and may be the constriction that limits the rate at which the lake water discharges to the aquifer. In all, 36 slots and 4 loops have been mapped in the caverns measuring a total of 279 feet in length.

Between 1999 and 2000, a total of over \$8 million was raised from local and state sources to restore Lake Jackson. By the end of the project, 50 years of accumulated muck, over 2,000,000 cubic yards, had been removed from the lake bottom. Since the muck removal project in 2000, Lake Jackson has languished in a rather empty state, being less than half full for most of the time, until filling maybe a year ago. Because of the extreme variation in water levels during this period the effects of the sediment removal in Lake Jackson were never fully evaluated. Now that the lake is full we will finally find out.

Lake Lafayette

- Final USEPA TMDL for Upper Lake Lafayette for nutrients (USEPA, 2012)
- State TMDLs for Upper Lake Lafayette for nutrients and dissolved oxygen (Wieckowicz et al., 2003)
- Alford Arm, Lake Piney Z, and Upper Lake Lafayette classified as impaired for dissolved oxygen (FDEP, 2016a)
- Contains sinkholes and seepage areas which discharge water to the UFA
- Goes dry during droughts

Lake Lafayette is the remnant of a Pleistocene river delta, over 10,000 years ago when sea levels were higher and Lake Lafayette became the coastal delta of an ancient river that ran approximately the course of the Alford Arm Tributary today. It was probably filled with more water from the melting glaciers. Dissolution processes culminated in the formation of a large lake drainage basin of 8,925 acres. The lake itself occupies 1,825 acres and includes a major sinkhole just north of the Cody Scarp at Fallschase.

The early settlers of Leon County called Lake Lafayette 'Prairie Lake'. This descriptive name tells a lot about how Lake Lafayette originally looked. It was not until nearby lakes were given to French settlers for helping in the American Revolution as part of the Lafayette Land Grant, that it became known as Lake Lafayette.

The Lake Lafayette basin is the most intensively developed of the larger lake basins in Leon County. This basin of 51,000 acres drains most of central and northern Tallahassee. Lake Lafayette is currently impounded into four hydrologically distinct units. It is the most modified major lake basin in North Florida and no longer functions naturally.

The Lafayette basin formerly functioned as a temporary lake, similar to Lakes Miccosukee and Iamonia, where water was frequently exchanged between the various basins now within the lake. Depending on rainfall patterns water would flow into or out of the lake. The large continuous basin was better able to absorb floodwaters than the smaller subdivided basins of today, and excess water had more avenues of escape, helping to diminish flooding.

Upper Lake Lafayette (ULL) is filled with urban storm water that continuously drains into the aquifer through a large permanent sinkhole at Fallschase (Wieckowicz, et al., 2003). The USEPA subsequently published a final federal TMDL for ULL for nutrients with specific limits for chlorophyll a, total phosphorus, and total nitrogen (USEPA, 2012). As a result of the earlier state TMDL (Weickowicz et al., 2003), a phosphorus-removal water treatment facility using alum was built on the major inflow which drains about thirty percent of urban Tallahassee. The 10 million dollar plus facility has only been in operation for a half year and does not appear to have been effective at remediating water quality problems in the lake. During the summer of 2016, ULL was covered with a bloom of the toxic cyanobacterium (blue green algae) *Microcystis*. A sample analyzed for the cyanotoxin microcystins measured at 714 ug/L. This is over 700 times greater than the World Health Organization's guideline for drinking water and 36 to 120 times greater than thresholds set by various states for recreational water bodies (USEPA, 2016).

Bradford Brooks Chain of Lakes

- Good water quality
- Contains sinkholes and seepage areas which discharge water to the UFA
- Goes dry during droughts

The Bradford Brooks Chain of Lakes (BBCL) is a dynamic chain of lakes totaling 342 acres surrounded by magnificent cypress trees. This chain of lakes is connected to the UFA by sinkholes. Lakes Bradford, Cascade, and Hiawatha are the largest lakes in the chain and are important recreational areas.

The waters of these lakes are very dark from tannic acid because, like the sinking streams, they drain some 3,000 acres within the Apalachicola National Forest via Bradford Brook. The pH of the water is usually less than five. This is a well-preserved natural area, and these lakes are typically very clean.

Periodically Lake Bradford receives storm water from the Lake Munson drainage through Grassy Lake from the West Drainage Ditch during high flow conditions. Lake Cascade also gets runoff from Capital Circle. The storm water is not tannic but is high in nutrients and algae. Lake Hiawatha is the most secluded and isolated of these lakes.

Lake Cascade has an active group of sinkholes, and has drained and refilled many times. The twin sinks in Lake Cascade look much the same today as they did at the turn of the century (figure I-8). Lakes Bradford and Hiawatha have had active sinks in the past, but

they have been inactive since the drought of 1999. The Lake Bradford sink (figure I-9) was active in 1956 when it drained the lake and the fish population became stranded in the sinkhole.



Figure I-8: Twin sinkholes in Lake Cascade (July, 2006, Seán McGlynn).



Figure I-9: Sinkhole in dry Lake Bradford photographed in 1956 (1956, Florida Memory, Archives of Florida, Red Kerce).

Killearn Chain of Lakes

- 4E impaired water classification of Lake Killarney for nutrients and un-ionized ammonia and Lake Kanturk for nutrients (FDEP, 2016b)
- Contains sinkholes and seepage areas which discharge water to the UFA
- Goes dry during droughts

The Killearn Chain of Lakes (KCOL) are natural karst lakes totaling 181 acres in surface area. Photographic evidence shows that these lakes are basically unaltered since they were mapped in the 1820's. When dry, as they were several times over the last decade, sinkholes are evident in the lakes (figure I-10). Notwithstanding the sinkholes, these lakes continually leak surface water into the underlying UFA via seepage through their bottoms.

The KCOL system periodically fills with storm water and then quickly becomes stagnant. Frequent toxic algal blooms, low dissolved oxygen, and fish kills occur here. These lakes flow into the Alford Arm Tributary and Lake Lafayette. These lakes have subsurface seepage which flows toward Wakulla Springs.

FDEP has classified two of these lakes as 4-E impaired waters (Ongoing Restoration Activities): Kanturk for nutrients and Killarney for nutrients and un-ionized ammonia (FDEP, 2016b). In early 2016 the Killearn Homes Association entered into this cooperative agreement with FDEP. They have agreed to try specific projects to fix the impaired water quality within 5 years, or else these two lakes will be listed as Verified Impaired Waters. So far, there has been no progress. These lakes were previously listed as having impaired waters for total nitrogen, total phosphorus, and fecal coliform bacteria.

The vegetation in the KCOL is not natural or native. A voracious invasive exotic macroinvertebrate herbivorous mollusk, the Channeled Apple Snail (*Pomacea canaliculata*) infests the lakes. The dominant vegetation is *Alternanthera philoxeroides*, commonly known as Alligator weed, which the snails find distasteful. The water in the lakes is commonly a dark green color due to blooms of potentially toxic cyanobacteria (blue-green algae) including *Microcystis* and *Anabaena*.



Figure I-10: Sinkholes in Lake Killarney (2011, Brad Trotman)

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Appendix II: Nitrate, Ammonia, Color, and Chlorophyll

Water quality parameters, other than total nitrogen, also were analyzed from the samples collected for this project. These analyses were not funded by the Fish and Wildlife Foundation of Florida tag grant.

Nitrate is considered a conservative pollutant in soils. It is not adsorbed by soils, but runs through relatively unimpeded. Attenuation of nitrates in soils can be zero and depends more on bacterial activity. Soils fix and bind phosphorus readily, sometimes with complete adsorption. However, in soils saturated with water, as in solution basins, the adsorption sites within the soils soil molecular complex can become saturated with phosphorus. Then there is no attenuation of phosphorus. There is very little data on the attenuation of corrected chlorophyll a or tannic color in water transported through karst soils. So, for the purpose of discussion, and to look at the magnitude of the possible pollutant loading of these compounds, we use the conservative attenuation rate of 20%, and a recharge rate on 10%, where these rates for many of these compounds may differ (table II-1 and figures II-1 through II-8).

Color and chlorophyll a are small organic molecules and, therefore, probably behave similarly to phosphorus. One would think the algae cells containing the chlorophyll would behave as particulates, getting stuck and filtered out between sand grains, but the algae cell wall is just a thin membrane that can easily be broken or degraded and the chlorophylls can go into solution and pass through the soils. Thus these pollutants behave rather similarly to nitrogen in saturated soils, as would be found in waterbodies, like karst lakes, where the water is constantly seeping.

Table II-1: Annual concentrations of the nitrate, ammonia, color, and corrected chlorophyll a.

Sinking Waterbody	Nitrate, Conc. (mg/L)	Ammonia, Conc. (mg/L)	Color, Conc. (PtCo Units)	Corrected Chlorophyll a Conc. (ug/L)	Years of WQ Data
Lost Creek	0.030	0.050	308.3	2.0	2014-2015
Lake Iamonia	0.036	0.032	83.5	16.2	2012-2015
Lake Miccosukee	0.025	0.020	40.0	11.9	2012
Lake Jackson	0.022	0.040	21.1	10.0	2012-2015
Lake Lafayette	0.023	0.024	29.3	43.9	2014-2015
Black Creek	0.030	0.050	300.0	1.8	2014-2015
Fisher Creek	0.029	0.049	276.8	1.6	2012-2015
Lake Munson	0.041	0.200	61.1	77.6	2012-2015
KCOL	0.022	0.100	24.1	10.3	2013-2015
BBCL	0.032	0.073	168.0	15.9	2012-2015

Nitrate Loading

Nitrate loadings were highest for Lost Creek (figure II-1), due to the volume of flow, and despite the fact that nitrate concentrations were rather low. When we looked at the loadings for all the sinking streams versus all the sinking lakes the loadings were more nearly equal (figure II-2). Both the sinking streams and the sinking lakes had relatively similar loadings of nitrates because the aquatic vegetation they host is very efficient at the uptake of nitrate.

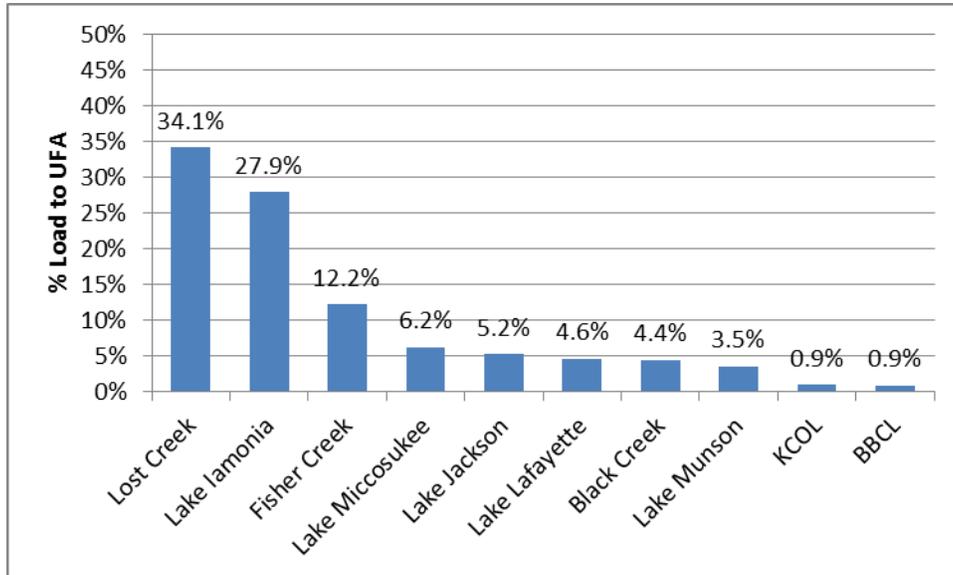


Figure II-1: Annual percent loadings of nitrate from individual sinking streams and sinking lakes in the Wakulla Springshed.

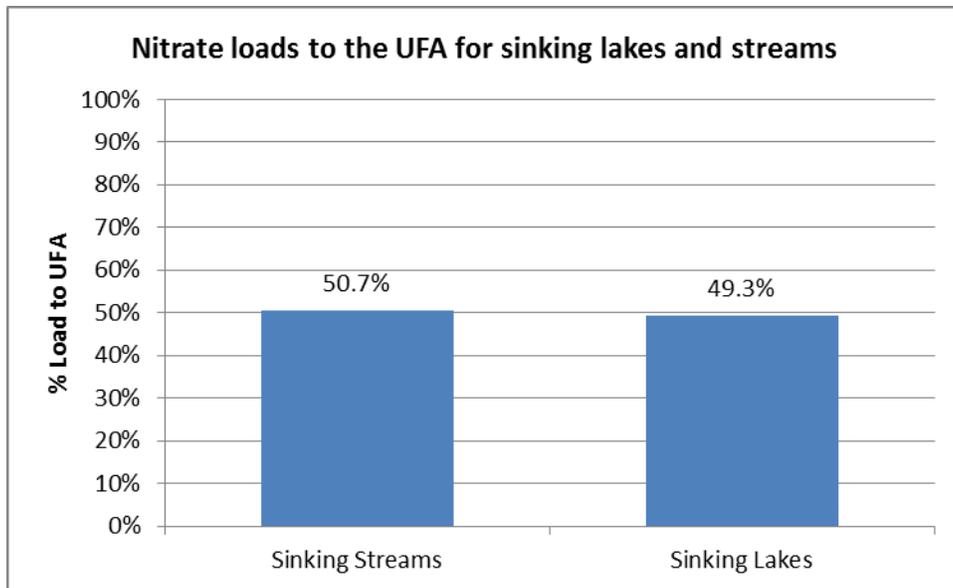


Figure II-2: Annual percent loadings of nitrate from sinking streams and sinking lakes in the Wakulla Springshed.

Ammonia Loading

The ammonia loading was also highest for Lost Creek (figure II-3), due to the volume of flow, and despite the fact that ammonia concentrations were rather low. Ammonia is second among all waterbodies for both ammonia and nitrates. Lake Munson ranks higher for ammonia (11.2%) than for nitrates (3.5%), and has moved from 5th among the lakes to 2nd. This is due to the high concentrations of ammonia found in that lake; FDEP has designated Munson Slough, the Lake Munson outfall, as impaired for ammonia toxicity. When we looked at the ammonia loadings for all the sinking streams versus all the sinking lakes the loadings were somewhat higher for the streams (figure II-4)

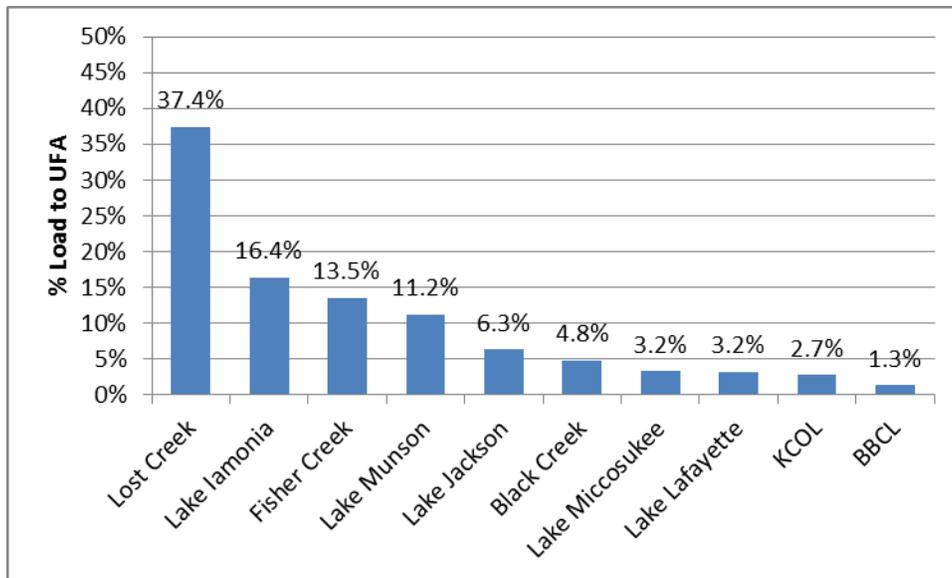


Figure II-3: Annual percent loadings of ammonia from individual sinking streams and sinking lakes in the Wakulla Springshed.

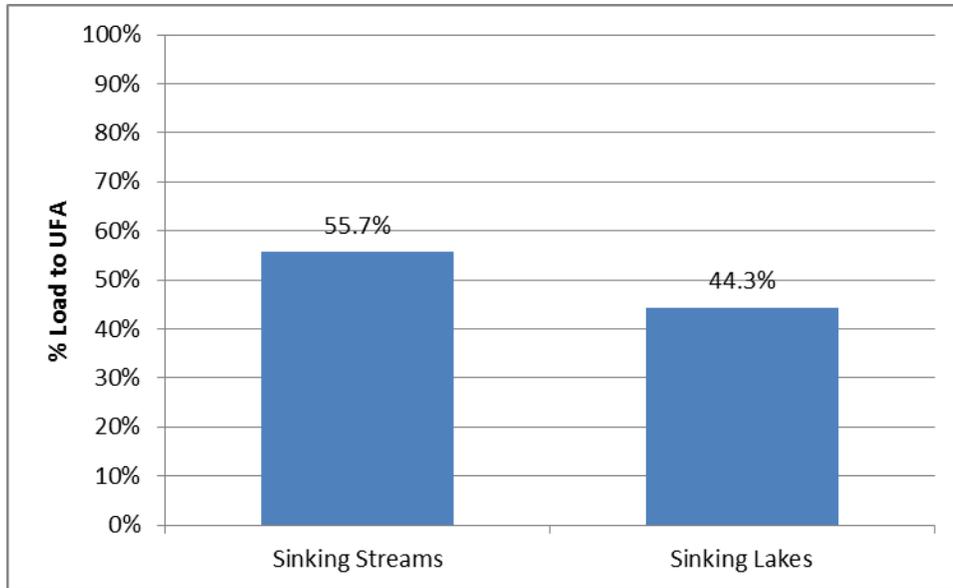


Figure II-4: Annual percent loadings of ammonia from sinking streams and sinking lakes in the Wakulla Springshed.

Color Loading

Color loading was highest for Lost Creek (figure II-5). Color loading of most of the lakes was about 64 times lower than Lost Creek with the exception of Iamonia. When we compare the loadings for all the sinking streams versus all the sinking lakes the stream loadings are substantially greater (figure II-6). Thus the sinking streams are responsible for most of the color loading to Wakulla Springs.

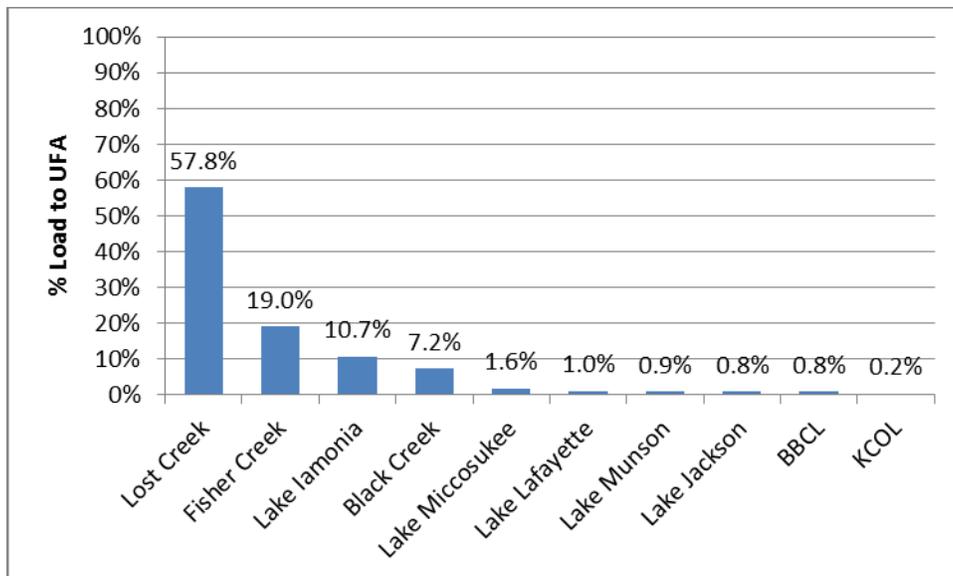


Figure II-5: Annual percent loadings of color from individual sinking streams and sinking lakes in the Wakulla Springshed.

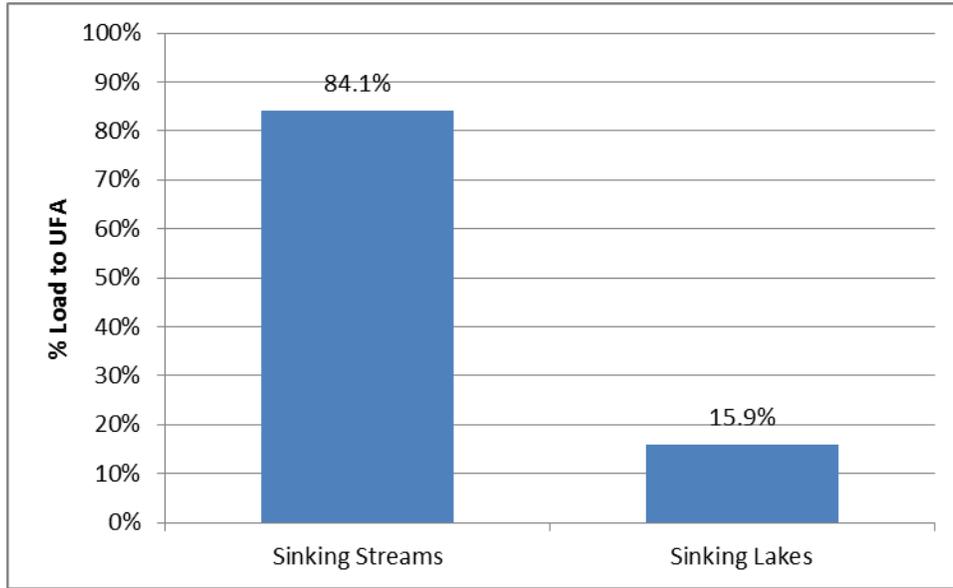


Figure II-6: Annual percent loadings of color from sinking streams and sinking lakes in the Wakulla Springshed.

Chlorophyll a Loading

Chlorophyll a loadings were corrected for chlorophyll degradation products (phaeophytin). Loading was highest in Lakes Iamonia, Munson, and Lafayette (figure II-7). All of the lakes, with the exception of the BBL and KCOL, were higher than any of the streams. The total loadings for the sinking streams are substantially lower than those from all of the sinking lakes because suspended algae have no chance to grow in flowing water (figure II-8). The sinking streams are also tannic and that color inhibits photosynthesis and plant growth. Thus the sinking lakes were responsible for most of the chlorophyll a loading to Wakulla Springs.

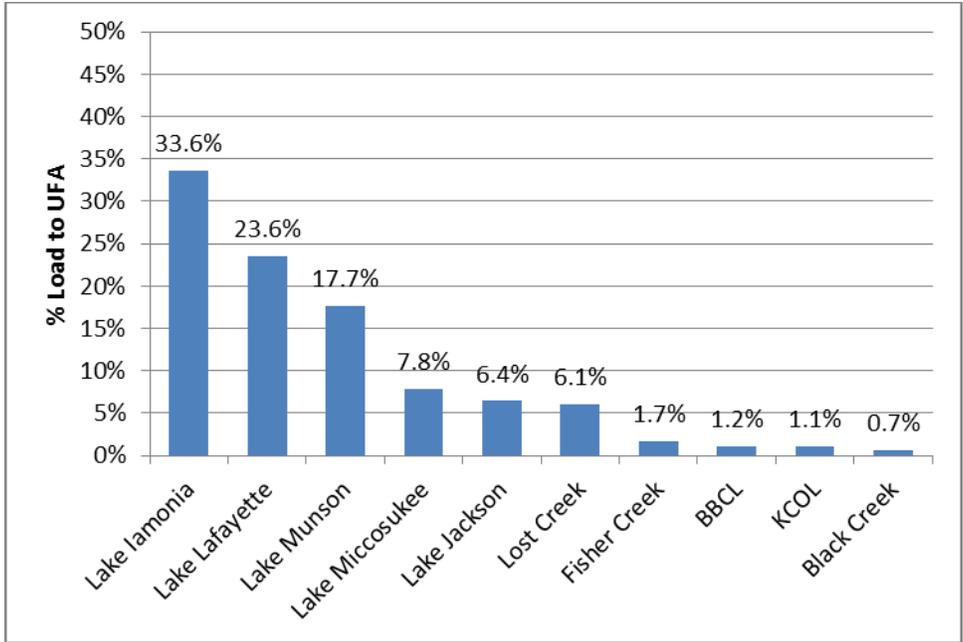


Figure II-7: Annual percent loadings of corrected chlorophyll from individual sinking streams and the sinking lakes in the Wakulla Springshed.

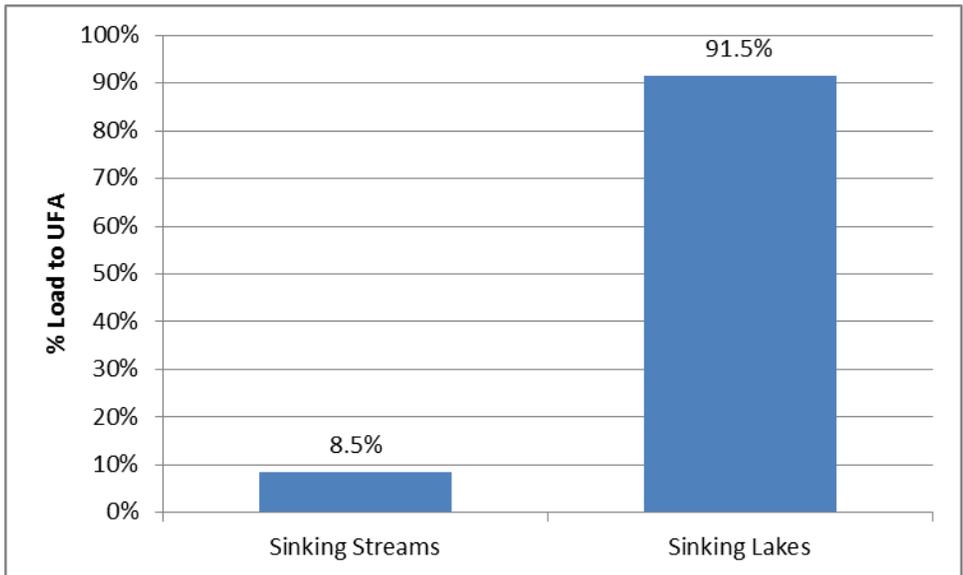


Figure II-8: Annual percent loadings of corrected chlorophyll in sinking streams and sinking lakes in the Wakulla Springshed.