Collaborative Research Initiative on
Sustainability and Protection of Springs [**CRISPS]**

Executive Summary

FINAL REPORT
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C R I S P S

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EXECUTIVE SUMMARY

ES.1 INTRODUCTION

The Floridan aquifer is Florida's most significant water resource. Two of the best indicators of aquifer health are the quantity and quality of water emanating from the ground as spring discharge. Florida's springs not only reflect the status of the aquifer, but they also influence the ecological health and integrity of many of the State's most significant surface water ecosystems. The springs themselves are outstanding aquatic resources with aesthetic qualities, geological attributes, and biological characteristics that render them magnets for tourism and sanctuaries for renewal of the human spirit.

Over the last five decades or more, many springs have experienced a reduction in discharge, increased nitrate concentrations, increased occurrence of nuisance algae and invasive aquatic plants, decreased abundance of native vascular plants, and concomitant alterations of fish and invertebrate communities. These changes threaten the ecologic and socioeconomic values of the springs and their downstream receiving waters.

In recognition of the ecological and economic significance of the Floridan aquifer and its associated springs, the St. Johns River Water Management District (SJRWMD) developed a Springs Protection Initiative (SPI) in 2013, with three major programs: projects, regulation, and scientific research. In support of the initiative's scientific research program, the University of Florida (UF) and the SJRWMD implemented the Collaborative Research Initiative on Springs Protection and Sustainability (CRISPS) in 2014. The overarching goal of CRISPS was to understand the relative influence of natural and anthropogenic factors that affect a key indicator of healthy spring ecosystems – the relative abundances of native vascular plants and nuisance algae. An improved understanding of manageable factors promoting the growth of nuisance algae can inform effective management of the Floridan aquifer and its associated springs.

A major spring vent is part of a much larger and more complex system than is apparent from casual observation. Its origins extend over large areas and its functioning connects the depths of the unseen and extensive Floridan aquifer to the land's surface. A complete spring ecosystem comprises a terrestrial subsystem that generates aquifer recharge, a groundwater subsystem that conveys that water, and a surficial aquatic subsystem (hereafter, a spring) where that water reemerges at the land surface. Effective management of springs and their downstream waters will require an understanding of all subsystems and their interactions. This understanding entails tracing the sources of water and dissolved constituents from the land's surface to the groundwater subsystem, tracking the transport and transformations that occur in the aquifer, and examining the myriad factors and processes that affect the biological structure and function of the surficial aquatic ecosystem. Of special interest to those engaged in CRISPS, and to scientists and managers more broadly, is an improved understanding of what controls the relative abundance and interactions of nuisance algae (including mat forming taxa and epiphytic species) and other submersed aquatic vegetation (SAV), native vascular plants in particular, which make up the primary producer community structure (PPCS) in springs.

The complex system represented by springs is affected by land use, soil characteristics, geology, hydrologic characteristics of the aquifer, surface water hydrology, nutrient transformations and transport in both groundwater and surface water systems, as well as trophic interactions in the springs. Therefore, a highly integrated research effort is required to understand the linkages among these characteristics and processes, controls on the natural system, causes for changes to the system, and support efforts to ameliorate undesirable anthropogenic effects. CRISPS is inherently interdisciplinary, and provides the integrated framework required to significantly advance our understanding of the Silver Springs system and spring systems more generally. This work focused on the Silver Springs ecosystem for several reasons. Compared to most other major springs in Florida, it has a long history of in-depth ecological study and a substantive database for some key ecological drivers. It has experienced an increase in abundance of nuisance algae and changes in fish populations. Finally, it is one of Florida's most prominent springs in terms of discharge, biological and economic significance.

CRISPS concentrated on three major objectives:

1. Improve the scientific foundation for management of nitrate loading to springs. Through observations, experiments and modeling, CRISPS extended our understanding of the: a) sources, nature, and patterns of nitrogen loading to the groundwater subsystem; b) spatial variation in the hydrologic conveyance rates within the Silver Springs springshed; and c) the transformation and loss via denitrification, for example, of nitrate moving through the groundwater subsystem to the springs.

2. Evaluate whether a reduction in nitrate concentrations/loads alone will be sufficient to restore the balance between filamentous algae and submersed vascular plants. CRISPS expanded scientific understanding of the influence of nitrate as a driver of primary producers through observation and experimentation.

3. Assess the relative influence and manageability of non-nitrate drivers controlling primary producers. CRISPS examined the influence of other potential drivers of primary production including physical drivers such as light, temperature, and current velocity, as well as nutrients other than nitrate and grazing by aquatic herbivores.

The CRISPS research team was organized into two major groups: the Springshed Supergroup and the Springs Ecosystem Supergroup. The Springshed Supergroup focused experiments and modeling on identifying sources of nutrients, particularly nitrogen, conveyed from the land's surface to groundwater, as well as transformation, loss, and transport of nitrogen through soils and groundwater to the spring vents. Nitrogen loading in springsheds varies in response to rainfall, temperature, season, rates and forms of nitrogen inputs, soil types, land use, and land cover. Transport of inorganic and organic forms of nitrogen to the spring depends on aquifer properties, the geometry of conduits and fractures, and transformation and loss in the groundwater system.

Similarly, the Springs Ecosystem Supergroup used both experiments and modeling to explore hydrodynamic, biogeochemical, biological, and ecological processes in the Silver Springs ecosystem. Inputs from the groundwater and watershed models are critical for predicting attributes of the physical-chemical environment that affect the functioning of the spring ecosystem (e.g., discharge and current velocities, depths, and nutrient concentrations). These inputs, along with other environmental characteristics such as light availability and dissolved oxygen concentrations, provide the template for biological responses, which can be described using mechanistic, empirical, or mixed models. Furthermore, internal controls arising from variation in biological drivers, such as grazing pressure on algae, also were considered. Based on the independent and interactive influences of physicochemical and biological processes, this group sought to assess the relative importance of these drivers in determining PPCS.

Key findings of this multi-disciplinary effort are summarized below. For details, the reader is referred to the nine, comprehensive, individual reports that comprise the complete study (Box ES.1).

ES.2 GENERAL CONCLUSIONS

The CRISPS research effort increased our understanding of the Silver Springs ecosystem specifically, and of Florida's springs in general. Many major and minor findings provide guidance for future management efforts. The salient conclusions relevant to each of the major research objectives listed below:

Objective 1. Improve the scientific foundation for management of nitrate loading to springs.

- **Land use patterns influence nitrate concentrations in soils.** Agricultural lands exhibit higher nitrate concentrations in their soils than urban landscapes, which, in turn, exhibit higher nitrate concentrations than either forests or wetlands. Agricultural and urban Best Management Practices (BMPs) that reduce the amount of nitrogen applied to the land's surface and improve the efficiency of assimilation by plants should reduce nitrate loading to springs.

- **Observations and modeling indicate that flow in conduits and fractures, rather than in porous media, dominates the delivery of water and solutes including nitrate within several kilometers of the springs**. Flows in conduits and fractures generate spatial heterogeneity in travel times for nitrate within the springshed. *In situ* measurements in the Floridan aquifer suggest that within a few kilometers of the springs, flows in conduits and fractures account for the vast majority of water movement, but only a very small portion of the volume of water in the aquifer. Although equivalent porous media matrix models may adequately simulate spring discharge, CRISPS modeling experiments highlight the value of including conduit networks when mapping vulnerability and targeting management interventions that will most quickly reduce nitrate concentrations in springs. A new calibrated Silver Springs model containing plausible conduit networks should enhance efforts to identify vulnerable areas of the Silver Springshed. Additional field measurements and modeling experiments would be needed to develop such a model.

- **Denitrification has the potential to remove a substantial fraction of the nitrate nitrogen load in the soils, vadose zone, and aquifer before it reaches the springs**. Rates and timescales for removal of nitrogen due to denitrification vary across the springshed. Efforts to reduce nitrogen loads from the springshed could focus on enhancing the necessary conditions in areas where the nature of the soils and subsurface strata (sands or limestone containing little organic matter) limit denitrification rates or areas in close proximity to spring vents. These areas are typical of the western, unconfined portions of the springshed, including the city of Ocala and surrounding urban areas.

Objective 2. Evaluate whether a reduction in nitrate concentrations/loads alone will be sufficient to reduce the occurrence of nuisance algae and restore the balance between benthic filamentous algae and submersed vascular plants.

- **Ecosystem primary production does not currently appear to be nitrogen limited in either Silver River (1.38 mg N L^{-1}) or Alexander Springs Creek (0.05 mg N L^{-1})**. Three lines of evidence support this conclusion: 1) present day rates of primary production are similar to rates observed at earlier times when nutrient concentrations, nitrate specifically, were lower (i.e., 1955 and 1980), and rates are slightly higher in Alexander Springs Creek than in Silver River despite far lower nitrate concentrations; 2) uptake rates for nitrogen that would support current primary production (growth of plants and algae) in Silver River are less than 1.5 % of the nitrogen load delivered to the system, and 3) experimental nitrogen enrichment did not stimulate gross primary production (GPP) or increased algal accrual in either Silver River or Alexander Springs Creek, and nitrate depletion in benthic chambers created concentrations near background levels, but had no effect on GPP in Silver River.

- **High concentrations of nitrate do not appear to inhibit SAV growth**. High nitrate concentrations have been hypothesized to influence PPCS by inhibiting growth of SAV. Results from both field measurements and experimental manipulations do not support this hypothesis.

- **These observations indicate that nitrate reduction alone is unlikely to restore PPCS**.

Objective 3. Assess the relative influence and manageability of non-nitrate drivers of primary producer community structure.

- **The velocity of water movement strongly influences PPCS.** A velocity of approximately 0.22 m s^{-1} represents an important threshold for epiphytic algal cover, although algae may be present above and below this threshold. Before 2000, velocities often exceeded this threshold in Silver River. Between 2000-2003 the stage-discharge relationship changed to yield higher stage and lower velocity for a given discharge. For example, at a discharge of 20 m^3 s^{-1} (~700 cfs), the existing regime yields mean channel velocities of approximately 0.16 m s^{-1} in the stream run just below the main spring, whereas the previous regime gave velocities of about 0.24 m s^{-1} at this location. This hydrologic transition and concomitant velocity change may have reduced sloughing of epiphytic algae, leading to higher algal biomass. It is important to note, however, that areas of the river with slower flow likely always contained epiphytic algae, even when mean channel velocities were higher. Colonization and removal of epiphytic algae does not appear to be hysteretic, so restoring higher velocities should reduce epiphytic algal cover on SAV.

- **Light and temperature are the dominant controls on community-level primary production and respiration.** Most of the spatiotemporal variation in GPP is explained by corresponding variation in light and temperature alone, and patterns in these drivers have not changed substantially in recent history. The stability in production and respiration rates through time, and strong evidence for abiotic controls on PPCS, provide strong support for the view that increases in primary production do not underlie an increase in nuisance algal biomass. Other factors and processes, e.g., scouring and grazing, appear more relevant in accounting for changes in the PPCS; an increase in the prevalence of nuisance algae specifically.

- **Thick and mobile benthic sediments represent important sources of non-nitrate nutrients.** Unlike most Florida springs, which are punctuated by limestone outcroppings associated with the Floridan aquifer, the bottom of the Silver River is completely covered by sediment over 6 m deep. These sediments are deposited rapidly (~ 2 mm yr^{-1}), and at one site (RM 0.7) up to 50 cm were deposited sufficiently rapidly that ^{210}Pb decay ($t_{1/2}$ = 22.3 years) was unobservable. The sediments are a mix of autochthonous and allochthonous materials, and they contain large amounts of organic carbon; nearly 50 % by weight where sedimentation rate was most rapid. Mineralization of organic carbon drives rapid denitrification, but the loss of nitrate N from the water column is balanced by the flux of ammonium N from benthic sediments, which, in turn, is likely oxidized to other combined forms of nitrogen including nitrate. The sediments are also important sources of other nutrients, including phosphorus (P), iron (Fe), and sulfide. Flux across the sediment-water interface, in stagnant areas of the ecosystem, may represent a relatively more important source of solutes than delivery by flowing water.

- **Native macrophytes and their epiphytes provide much of the energy that is transferred to higher trophic levels.** Benthic filamentous algae (one form of nuisance algae) do not contribute substantially to production at higher levels in the aquatic food web. Herbivorous insect larvae, however, do appear to use these algae as food. Because nuisance algae are consumed primarily by these emergent insects, it is likely that much of this secondary productivity is exported to the surrounding terrestrial environment. In essence, nuisance algal mats in Silver River, and likely other spring systems, may be largely decoupled from the aquatic food web. Experimental work provided little evidence that predators mediate the impacts of grazing on plant and algal dynamics in Silver River, i.e., strong top-down influences were not apparent.

Based on findings, as summarized above, land use activities have a profound influence on soil nitrate concentrations and subsequent delivery of nitrate to the groundwater subsystem. Nitrate removal rates and hydrologic conveyance are, in turn, determined by soil properties and physical characteristics of the aquifer itself. Uncertainty remains regarding the precise location of conduit networks within the Silver River springshed. Empirical data and modeling efforts suggest, however, that such networks likely account for the vast majority of groundwater movement and solute transport and thus merit further investigation.

With regard to the surface water subsystem, a central question addressed as part of the CRISPS effort was whether nitrate reduction alone might be sufficient to affect a change in PPCS; specifically, a reduction in the abundance of nuisance algae. From an ecosystem-level perspective, it is unlikely that a reduction in nitrate alone will affect a change in the PPCS in the Silver River spring ecosystem. In fact, it appears that primary production in the Silver River spring ecosystem is currently relatively insensitive to large variations in nitrate concentrations because the availability of nitrate is primarily driven by the discharge and nitrate mass flux far exceeds the demands of primary producers. Water velocity, on the other hand, clearly influences PPCS in the Silver River and was identified as a primary determinant of epiphytic algal cover on native vascular plants. Algal abundance on vascular plants at any given location and time is a reflection of growth dynamics and losses. Sloughing of epiphytic algae represents a loss term due to physical processes associated with water movement, e.g., shear stress and turbulence. Grazing can also result in algal loss. Regarding the impacts of grazers on algal abundance, stable isotopic signatures clearly indicated that mat-forming, benthic filamentous algae in the Silver River is consumed primarily by emergent insects and not by other common grazers in the system. These other grazers, i.e., gastropods, turtles and some fishes, consume native macrophytes and/or their associated epiphytic algae (which, if left unchecked, can accrue to nuisance levels). The interactive effects of flow velocity, nutrient delivery and grazers on the composition and abundance of epiphytic algae merit additional study.

In general, management of a spring will involve each of the three major subsystems of the complete ecosystem: the terrestrial subsystem (the springshed), the groundwater subsystem (the shallow, intermediate, and Floridan aquifers), and the surficial aquatic subsystem (the springs). In support of a holistic view of spring ecosystems, summaries of the key findings and outcomes from all projects are provided below.

ES.3 SPRINGSHED PROCESSES

This element of the program elucidated the sources of nitrogen within the Silver Springs springshed, developed models of flow in conduits and fractures for the Upper Floridan aquifer within the springshed, and examined the transport and loss of nitrogen within the aquifer system. One of the salient difficulties in understanding and managing springs is that their source water flows through a concealed and complex system of porous limestone that includes fractures and conduits. The karst system of the Floridan aquifer typically has been modeled as an equivalent porous media. It is well known; however, that karst contains fractures and conduits that transmit water at rates much higher than those characteristic of the surrounding porous rock. These more direct connections to spring vents are distributed heterogeneously, creating regions where water and solute travel rapidly to the vents. These regions create "hot-spots" within the springshed where nitrate applied to the land is transported more rapidly to springs with little opportunity for removal, e.g., via denitrification.

ES.3.1 Groundwater Hydrology: Conduit and Fracture Flow Modeling

Modeling was used to examine how conduits might develop in the aquifer and how spatial variation in the network of conduits could affect delivery of water and nutrients to Silver Springs. The overall goals were to determine the significance of conduits in the transport of water and solutes (particularly nitrate) to Silver Springs and to estimate the uncertainty associated with predictions about transport and flow resulting from uncertainty about the geometry of conduits. The results of Monte Carlo simulations indicate that incorporating plausible conduit networks within a calibrated Silver Springs model would help identify vulnerable areas in the springshed that could be targeted for management interventions leading to more rapid and effective reductions of nitrate in the springs. Specific results of this work (Section 2 of this report - Graham et al.) indicate that:

- Conduit networks that evolved from models based on physicochemical equations to produce first magnitude springs demonstrated a range of physical configurations. However, for the ensemble of networks that produced first magnitude springs, conduits tended to develop in topographic lows that drained nearby high regions. In general, these networks exhibited high connectivity and relatively rapid transport along a north-south axis within the springshed.
- For the ensemble of conduit networks that produced first magnitude springs, the uncertainty surrounding the magnitude of flow and concentration of solutes arriving at the spring vent after a unit pulse applied to the land's surface was relatively low, and the results were consistent with field observations. These outcomes suggest a high level of consistency regarding aggregated flow and transport of solutes across the variable conduit networks.
- Simulations of reverse transport across the ensemble of conduit networks that produced first magnitude springs predicted large, vulnerable regions in the springshed (i.e., areas with short travel times from the land surface to the spring) with relatively low uncertainty. Vulnerable regions tended to be topographic lows in the central part of the domain where conduits developed. The spatial distribution of these vulnerable regions was significantly different from the concentric ellipses which would be identified using an equivalent porous media model.
- Results of this modeling experiment highlight the value of including conduit networks when mapping vulnerability and planning management interventions that will reduce concentrations of contaminants in spring flows.
- Monte Carlo analysis of backwards tracer pulse experiments conducted on a new calibrated Silver Springs model containing plausible conduit networks should enhance efforts to identify vulnerable areas of the Silver Springshed that could be targeted for management interventions.

ES.3.2 Springshed Hydrology: Nitrogen Transport and Loss

The goal of this work was to gather hydrogeologic data in the field. Passive flux meters (PFMs) within wells that reached the Floridan aquifer measured flows of water and solutes in order to identify portions of the aquifer that deliver more significant quantities of water and solutes to the spring. These measurements were employed subsequently to examine the characteristics of flow and natural attenuation of solute loads, with special emphasis on nitrate (for additional details, see Section 3 of this report - Jawitz et al.). Key findings are:

- A wide distribution of groundwater velocities were measured *in situ* using PFMs in the Floridan aquifer, with the lowest velocities representative of matrix flow and the highest velocities likely representing contributions from fractures and conduits. Measured groundwater velocities ranged from 2.6 to 10.9 cm d^{-1} with a mean of 6.2 cm d^{-1}. These velocities are consistent with slow flow through the rock matrix.

- Nitrate-N fluxes in the rock matrix were below detection limit of the PFM technique. However, measured phosphate fluxes were in the range of 0 to 0.8 mg PO_4-P $_{m^{-2}}$ d^{-1} and sulfate fluxes ranged from 1.3 to 31 mg SO_4-S m^{-2} d^{-1}.
- A new karstic borehole device (KBHD) fabricated for this study measured groundwater and solute flux in fracture and conduit zones. The resultant fluxes were more than 50 times greater (mean = 3.1 m d^{-1}) than those previously measured with PFMs in the aquifer matrix.
- These data combined with velocities measured in tracer tests, the known flux from Silver Springs, and the aquifer dimensions suggest that within approximately 5 km of the spring vent, matrix flow contributes only approximately 10 % of the discharge from Silver Springs. Non-matrix flow, which includes fractures and conduits, is therefore surmised to contribute approximately 90 % of the water discharged from Silver Springs within this distance. The relative contribution of non-matrix flow diminishes slowly with distance from the spring vent.
- *In situ* nitrate attenuation also was evaluated in five wells with push-pull tests and the KBHD. In three of these wells, nitrate was not detected while two wells had mean mgNO_3-N L^{-1} concentrations of 0.77 and 2.2 mg L^{-1}, respectively. In the two wells with measurable nitrate, nitrate was not lost during the push-pull tests, with similar rates of recovery for both non-reactive (Rhodamine) and reactive (KNO_3) tracers indicating that denitrification at these locations was below the detection limit of this technique. However, in the wells where background nitrate and oxygen concentrations were low, recovery of nitrate in the push-pull tests was approximately 40 % less than the recovery of the non-reactive tracer. This loss of nitrate suggests redox conditions suitable for denitrification.

ES.3.3 Springshed Biogeochemistry: Nitrogen Transformations

In addition to the amount of nitrate carried in flowing water, biogeochemical transformations of nitrogen compounds in the soil, vadose zone and surficial aquifer determine how much nitrate enters the Floridan aquifer. The goal of this project was to trace nitrogen from sources within the springshed through the vadose zone and aquifer to discharge at the spring vent. Laboratory and field measurements were coupled in various ways to determine concentrations of nutrients, microbial composition, and denitrification rates in profiles through the soil and vadose zone, as well as concentrations of nutrients, ratios of stable isotopes for nitrate, and concentrations of dissolved gases in groundwater (for additional details, see Section 4 of this report - Inglett et al.). Key findings are:

- Nitrate concentrations in soils varied among land uses, and they ranked in the order of agriculture>urban>forest≥wetlands. Thus, patterns in land use point to patterns in surficial loading of nitrogen.
- Results suggest the potential for significant denitrification during transit through surface soils to groundwater as evidenced by changes in the isotopic composition of nitrate-N and oxygen, measured rates of denitrification, and abundance of denitrifying microorganisms in profiles through the soil and vadose zone. Surface soils containing more organic matter are the most significant sink for nitrate, however, layers of relic peat and deposits of marine groundwater demonstrate the potential for high rates of denitrification deeper in the system.
- Laboratory studies with the most abundant soil type in the springshed (sandy soils with little organic matter) showed that temperature exerted the strongest control on soil denitrification. Across all land uses, denitrification increased with increasing temperature regardless of

whether water filled pore spaces or concentrations of nitrate or organic carbon were high. These laboratory incubations also indicated that nitrate was converted to ammonium at higher temperatures, particularly below pastures amended with manure.

- Direct measurements confirm low rates of denitrification in samples of limestone from the aquifer, but estimates based on concentrations of dissolved gases from the east and west Mammoth vents indicate that approximately 17 to 43 % of the nitrate load to the aquifer was lost through denitrification. Much of this apparent denitrification could occur in isolated surficial aquifers (e.g., peat layers) and areas of mixing with deep, more marine-based groundwater.
- Stable isotope values for nitrate-N and oxygen from profiles of the soil and vadose zone indicate that caution is warranted when attributing the source of nitrate in groundwater to land uses. Nitrification and denitrification, as well as interactions of nitrate with soil particles, all affect the isotopic signature of leached nitrate. Isotopic signatures from at least one site indicated potential contributions from multiple sources within a single profile.
- The amount of excess N_2 and accompanying changes in isotopic ratios for nitrate nitrogen and oxygen in samples from wells and the Mammoth vent complex indicate that most of the nitrogen in the unconfined, western springshed originates from a common source, with $\delta^{15}N$ and $\delta^{18}O$ signatures of approximately 6-7 ‰. These signatures likely represent more organic sources, such as wastewater, manure, or soil N, but caution should be used until additional analyses can better establish this end member.

ES.4 SPRINGS ECOSYSTEM PROCESSES

ES.4.1 Hydraulics and Hydrodynamics

The objectives of the Spring System Hydrodynamics/Hydraulics work order were to: 1) yield a more thorough understanding of the distributions of velocities and residence times in the Silver River's channel , including quantifying the location and magnitude of transient storage and exchange; 2) identify critical shear stresses for the entrainment and detachment of epiphytic algae; and 3) link these findings to three-dimensional modeling with a focus on how SAV impacts velocities, residence times, and the stage-discharge relationship (for additional details, see Section 5 of this report - Kaplan et al.). Key findings are:

- Breakthrough curves (BTCs) fit to measured data delineated flow paths and estimated reach-scale hydraulic properties of the Silver River for five dates that had differing hydraulic conditions. These results also provided valuable data for calibrating and validating the Environmental Fluid Dynamics Code (EFDC) model.
- Reach-scale velocities and mixing parameters measured via dye releases were variable in time and space, illustrating how the flow regime of the Silver River changes with different boundary conditions (spring flow and downstream river stage), as well as with in-channel properties such as SAV cover and density. Such variation impacts in-channel hydrodynamics and likely affects biogeochemical transformations in the river's advective and transient storage zones.
- Mixing parameters also were variable across experiments, illustrating differential mixing mechanisms across seasons and boundary conditions. Dispersion and transient storage were generally greatest when mean velocity was low and downstream stage was high. Beyond

empirical modeling, comparison of measured BTCs in beds of vegetation and the adjacent main channel suggests that vegetation can serve as zones of transient storage.

- Experimental approaches identified thresholds for critical velocity and shear stress below which algal biomass accrual increased.
- Data from the Florida Springs Synoptic Study, the Silver River, Gum Slough, and several coastal springs yielded an overall mean critical threshold for algal sloughing of 0.22 m s^{-1}. Mean critical shear stress for algal sloughing in the Silver River was 0.35 N m^{-2}, and the mean critical velocity threshold estimated to disrupt SAV (*Vallisneria americana* and *Sagittaria kurziana*) was 0.33 m s^{-1}.
- Models that include the observed stage/discharge shift suggest that under historic conditions, the mean velocity in the main channel near the spring was approximately 0.24 m s^{-1}, greater than the critical threshold for algal sloughing. Under the current stage/discharge relationship, the mean velocity in this location is predicted to be < 0.16 m s^{-1}, significantly lower than historic velocities and the critical velocity. This finding could, in part, explain algal biomass proliferation in some areas of the spring run.

ES.4.2 Springs Ecosystem Physicochemistry

This portion of the project quantified benthic sources and sinks of nutrients and characterized nitrogen dynamics and metabolism. This was accomplished through three sub-projects:

ES.4.2.1 Nitrogen Dynamics and Metabolism

Elevated nitrate concentrations have been invoked to explain increasing algal abundance and declining SAV health across springs. In this research element, four lines of inquiry evaluated this hypothesis, emphasizing spatial heterogeneity within spring systems and contrasting patterns across two springs with dramatically different nitrate concentrations (Silver River and Alexander Springs Creek) (for additional details, see Section 6 of this report - Cohen et al.). Key findings are:

- High resolution time series data for pH, dissolved oxygen (DO), nitrate, and phosphate were used to estimate ecosystem metabolism in the open channel as well as uptake of nutrients by autotrophs in 3 reaches along the Silver River and 1 reach along Alexander Springs Creek.
- Significant diel variation was observed for nearly all solutes in the Silver River, consistent with strong temporal forcing from solar insolation. Time series of solute concentrations were used to estimate GPP and ecosystem aerobic respiration (ER). Observed rates of primary production were consistent with historical rates recorded in the 1950s and 1980s, with net autotrophy in the upper river (GPP > ER), net heterotrophy in the lower river (GPP < ER), and similar temporal variation for both GPP and ER. In Alexander Springs Creek, where nitrate-N concentrations remain near background levels (0.05 mg NO_3-N L^{-1}), and below those measured in the Silver River in the 1950s, GPP was slightly but not significantly higher and ER was slightly but not significantly lower than in Silver River.
- Using high resolution nitrate-N measurements, we determined that denitrification is the dominant N mechanism leading to loss of nitrate-N, with mean rates of 0.22 g N m^{-2} d^{-1} Autotrophic uptake (i.e., assimilation by plants) accounted for 0.06 g N m^{-2} d^{-1} or about 20 % of the gross loss. The assimilation flux of N equals 1.4 % of N delivered from the spring vents.

- Data on algal and SAV cover along the entire length of the Silver River showed that SAV cover was generally high (>75 % cover at nearly 90 % of 100 sites) while algal cover was more variable. Spatial variation in algal cover was best explained by negative correlations with SAV cover (which suggests inhibition), distance downstream, and surface water velocity.
- None of the parameters characterizing Silver River water chemistry provided significant explanatory power for algal cover, though algal cover was weakly and positively associated with some sediment properties (i.e., concentrations of Calcium (Ca), P, and magnesium). Cover of SAV declined with increasing concentrations of Ca in the water column, concentrations of chloride in the water column and porewater, and clay content of the sediment.
- Measurements of metabolism in benthic chambers confirmed that light availability was the dominant control on GPP. Nutrient enrichment (N, P, and Fe) yielded no significant effects on GPP in benthic chambers or algal growth rates on experimental tiles. Nitrate dynamics within the benthic chambers documented denitrification as the dominant process contributing to nitrate loss according to nearly 1st order kinetics, with assimilation by plants and algae accounting for a smaller flux that more closely follows 0th order kinetics (i.e., concentration independent). GPP was independent of (uncorrelated with) nitrate-N concentration.
- In Silver River, where *Vallisneria americana* and *Sagittaria kurziana* are both present, their growth rates were similar; Alexander Springs Creek only had *V. americana*, with mean growth rates nearly identical to plants in Silver River. Single variables yielded modest and inconsistent relationships with SAV growth, but multivariate models explained 60 % of variation in SAV growth, with key parameters being forest canopy cover, algal cover (for *Vallisneria* only), concentrations of soluble reactive phosphorus (SRP) in porewater, and redox conditions in the sediment.

ES.4.2.2 Nitrate Inhibition of Submerged Aquatic Vegetation

In response to observations of declines in SAV abundance and productivity in several Florida springs, an investigation was initiated to determine if high concentrations of nitrate-N (NO_x-N) can inhibit SAV growth. The potential for such inhibition follows from the hypothesis that two dominant SAV species, *Vallisneria americana* and *Sagittaria kurziana*, have not yet evolved a metabolic mechanism to turn off nitrate reductase, an enzyme that converts nitrate into ammonia. Because ammonia is phyto-toxic at elevated concentrations, it must be utilized rapidly, predominantly in protein synthesis. This process requires energy from metabolism of photosynthate, and under elevated nitrate availability, it could produce a significant energetic burden on SAV. In an effort to validate field observations by other researchers, mesocosms constructed for this work also were utilized to investigate the role of dissolved oxygen stress (hypoxia) on invertebrate grazers and the effects of flow velocity on the proliferation of epiphytic algae. Key findings of this study are presented below (for additional details, see Section 7 of this report - Osborne et al.).

- Results of this study do not support the hypothesis that elevated nitrate concentrations have a negative effect on the physiology of SAV in spring ecosystems.
- The two species responded differently to increased nitrate. The response of *V. americana* tended to be increased growth of both roots and shoots, while *S. kurziana* tended to show increased shoot production as nitrate increased.

- Nitrate reductase activity (NRA) in SAV tended to be greatest in roots for *V. americana* and in shoots for *S. kurziana,* further suggesting significant physiological differences between these species. Both species were proficient at nitrate uptake and incorporation into tissues, as indicated by decreased carbon to nitrogen ratios.
- Results suggest that four species of grazers experience hypoxic stress below 2 mg O_2 L^{-1}. The gastropod *Viviparus georgianus* was observed to be the most sensitive to low DO concentrations, with a threshold of 2.7 mg O_2 L^{-1}, while the grass shrimp *Palaemonetes paludosus* remained functional to 1.6 mg O_2 L^{-1}. Exposure to increased nitrate did not alter thresholds for hypoxic stress for *E. floridensis* and *T. granifera*. These findings suggest that the current frequency of hypoxic events (DO <2.0 mg O_2 L^{-1}) may reduce the abundance and activity of grazers.
- Shear stresses were observed to dramatically decrease algal growth and recruitment at velocities of 0.25 m s^{-1} and higher. While algal growth clearly was related to velocity, scouring of established epiphytic algal biomass did not exhibit any pattern potentially due to friction caused by SAV blades and steep velocity profiles.

ES.4.2.3 Benthic Sources and Sinks of Nutrients

Benthic sediments in streams act as biogeochemical reactors that change the chemical compositions of porewater relative to the overlying stream water. Biogeochemical reactions could thus provide an important source of solutes to stream water leading to effects on benthic and lotic ecosystems. However, impacts on stream water chemistry depend on the magnitude of fluxes of solutes to and from porewater, which is driven by the difference between concentrations of solutes in stream water and porewater and transport mechanisms, e.g., whether from advection of water and/or diffusion of solutes. Objectives of this study were to: 1) evaluate the distribution and chemical composition of sediments; 2) measure physical and hydraulic characteristics of the sediment; 3) assess the biogeochemical reactions in the sediment and their impacts on porewater compositions; and 4) estimate potential impacts of fluxes of solutes between bottom sediment and the river. Key findings from this study are presented below (for additional details, see Section 8 of this report - Martin et al.):

- Thick sedimentary deposits were found along the length of the Silver River. These sediments may have been deposited when the system was a quiescent lake and/or by flowing water. Excess ^{210}Pb in sediment cores indicated a high and constant rate of sedimentation that ranged from 1.6 to 2.2 mm yr^{-1}. This excess ^{210}Pb indicated that if sediments were originally deposited in a lake, they are being reworked by the river. Much of the inorganic sediment originated from erosion of the highlands to the west.
- The sediments comprise shell hash and sandy layers interbedded with fine grained layers rich in organic carbon. Some of the organic carbon was allochthonous, which represented a new source of nutrients to the river. The sediments were found to act as a barrier to flow into the river from the underlying Upper Floridan aquifer, except where water discharges from spring vents.
- Hydraulic conductivity of the sediments ranged from 5.5×10^{-7} to 6.2×10^{-3} m s^{-1}, similar to values expected from gravel beds. Horizontal hydraulic conductivities were higher than vertical hydraulic conductivities by factors from 1.1 to 25. Horizontal hydraulic conductivities were considered representative of the sandy shell layers, which may act as preferential flow paths to the channel if they are continuous. The distribution of such

continuous layers could not be determined with the limited distribution of sampling in this study. Head gradients were oriented from the sediment to the river through the entire 2-yr period of monitoring, which suggests groundwater flowed continuously to the river. Head gradients were low, which limited average horizontal and vertical flow rates to 1.4 and 0.4 cm d^{-1}, respectively.

- Biogeochemical reactions in the sediment are dominated by redox reactions, and porewater chemistry profiles that indicated that redox conditions extended to methanogenesis. However, each sampling site had unique chemical gradients. The biogeochemical reactions created concentration gradients in which maximum concentrations of solutes could be more than 100 times greater than concentrations in the river. Solutes produced by these reactions could be important inputs to the river, unless precipitated at the sediment-water interface, as would be expected as dissolved Fe(II) is oxidized to solid Fe-oxides.
- Concentration gradients created by the biogeochemical reactions drove diffusional fluxes of ecologically important solutes from the sediments to the river, including ammonium (NH_4), SRP, Fe, Mn and HS^-; whereas, nitrate was lost to the sediments from the water column. In addition, the hydraulic conductivities and head gradients indicated that flow also transported solutes to the river, although the estimated advective fluxes for all solutes were lower than diffusive fluxes. The total benthic flux (advection and diffusion) for NH_4-N, SRP, Fe, and Mn represented 12, 4, 12, and 5 % of the load from the spring. All sulfide originated from benthic fluxes. Depending on mixing with the overlying water column and residence time in stagnant zones, these fluxes may contribute more to macrophyte and algal growth than these percentages suggest.

ES.4.3 Springs System Biology - Trophic Interactions

Major objectives of this study were to: 1) identify the major algal grazers and their consumers; 2) determine algal growth relative to grazing rates of small grazers; and 3) assess the potential for top-down (consumer) control of key grazers that were identified as part of objectives 1 and 2. Natural abundances of stable carbon and nitrogen isotopes (8^{13}C and 8^{15}N) were employed as tracers to identify pathways of energy flow and material transport in Silver River. Manipulative field experiments assessed algal grazing and the influence of predators on those rates. Key findings are presented below (for additional details, see Section 9 of this report - Frazer et al.):

- In the Silver River, 8^{13}C and 8^{15}N values together with predictions from empirical models clearly indicate that native macrophytes and their associated epiphytes fuel much of the secondary production that, in turn, supports a diverse assemblage of organisms that occupy higher trophic levels.
- Nuisance filamentous algae do not contribute substantially to the diet of key consumers, such as gastropods, turtles and large herbivorous fish. Instead, it appears that a small number of insect larvae (i.e., trichopterans and chironomids), amphipods, and smaller omnivorous fish (i.e., shiners and darters) heavily exploit nuisance algae as a food source (contributions to diets > 30 %). Because nuisance algal production is consumed predominantly by emergent insects, it is likely that much of this production is exported to the surrounding terrestrial environment upon emergence. In essence, nuisance algal mats in Silver River, and likely other spring systems, may be largely decoupled from the broader aquatic food web. This is a dynamic that merits further investigation as it may fundamentally impact energy flow and material transport at the watershed scale.

- Alligators in the Silver River rely heavily on gastropods and crustaceans to support metabolism and growth. This finding has profound implications for any effort to model the river's food web. Previous models have considered alligators to be top/apex predators that mainly consume fish and other vertebrates occupying intermediate trophic levels. In other ecosystems, alligators are known to both directly and indirectly affect key ecosystem processes through their interactions with prey and the environment. Integration of these novel data and insights into food webs will help to refine our understanding of how predation and top-down pressures influence community dynamics within these complex ecosystems.
- Field experiments provided little evidence of predator-mediated impacts on plant and algal dynamics in Silver River; i.e., strong top-down influences were not apparent. Thus, management activities focused on reducing abundances of higher-level organisms in the system are not likely to result in marked changes in the PPCS.

For detailed information, the reader is referred to final work order reports (2014 - 2017) presented in this report (Figure ES.1; see below).

CRISPS: Work Orders- 2014 - 2017

Springshed Supergroup

Work Order # 1: Nitrogen Biogeochemistry: Sources, transformations and loss of nitrogen from land surface to springs. Patrick Inglett, pinglett@ufl.edu

Work Order #4: Groundwater Hydrology: Conduit and Fracture Flow Modeling.
Wendy Graham, wgraham@ufl.edu

Work Order #6: Springshed Hydrology: Transport and Loss of Nitrogen within the Upper Floridan Aquifer in the Silver Springs Springshed. James Jawitz, jawitz@ufl.edu

Spring Ecosystem Supergroup

Work Order #2: Silver River Hydraulics and Hydrodynamics
David Kaplan, dkaplan@ufl.edu

Work Order #3: Physicochemistry: Benthic Sources and Sinks of Nutrients and Nitrogen Dynamics and Metabolism.
Matt Cohen, mjc@ufl.edu
Jon Martin, jmartin@geology.ufl.edu
Todd Osborne, osbornet@ufl.edu

Work Order #5: Biology: Trophic Interactions.
Tom Frazer, frazer@ufl.edu

Figure ES.1. List of work orders of the CRISPS project