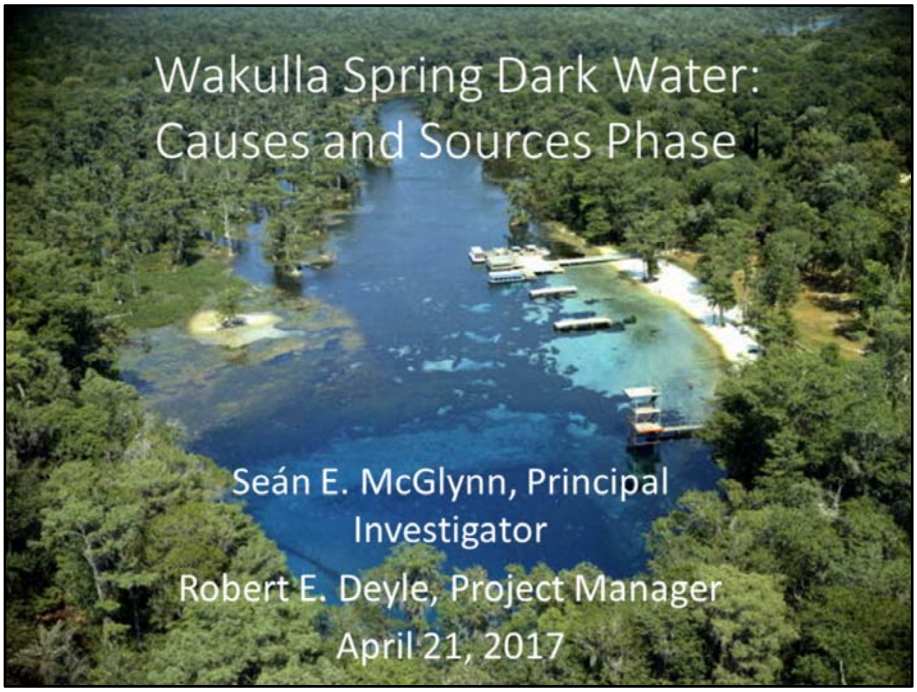
Wakulla Spring Dark Water:
Causes and Sources Phase
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Project Objectives

- Determine causes and sources of more prolonged "dark water" conditions experienced at Wakulla Spring
  – Define light absorption properties of pigments in water of Wakulla Spring and in water from karst features which recharge the spring
  – Document hydrogeological attributes of the Wakulla Springshed that may also contribute to those conditions
- Identify practical management strategies that might be developed to mitigate the problem

Approach

- August 25, 2015 – September 30, 2016
- Analysis of daily grab samples from Wakulla Spring for
  - true color (light absorbance at 465 nm by tannins)
  - specific conductance
  - nitrates
- Weekly in situ measurement at the spring of
  - light transmittance with depth – full visible spectrum radiometry (400-700 nm) and spectral radiometry by nanometer (200-900)
  - Secchi disk visibility depth

Approach

- Analysis of weekly grab samples from spring for
  - true color (light absorbance at 465 nm by tannins)
  - color absorbance for visible spectrum (400-700 nm)
  - corrected chlorophyll (chl a, b, and c minus phaeophytin)
  - phaeophytins(degraded chlorophyll)
  - specific conductance
  - nitrates

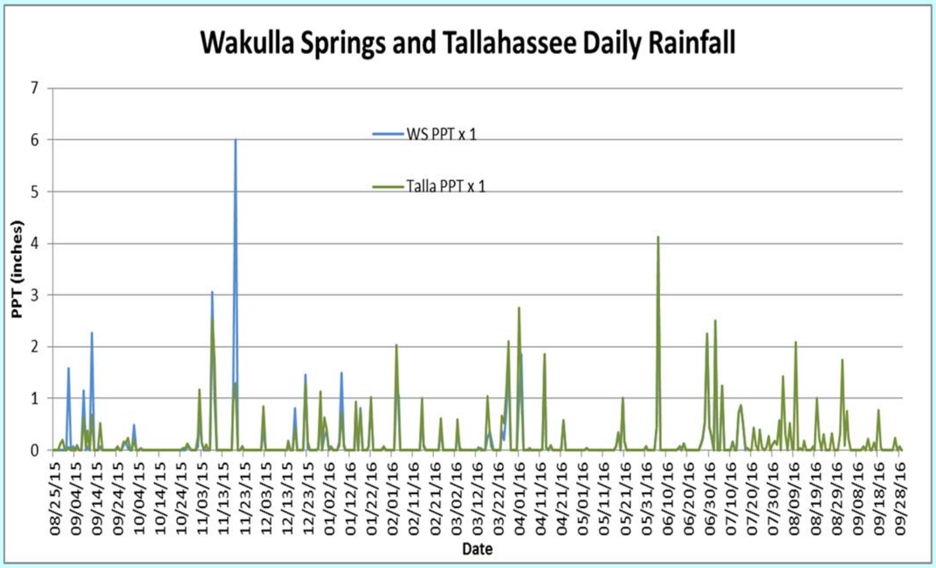
Approach

- Sampling for eight light/dark events at Wakulla Spring, Spring Creek, and major karst lakes and streams for
  - true color
  - color absorbance
  - corrected chlorophyll
  - phaeophytin
  - specific conductance

Approach

- Light/dark event sample sites:
  - Sinking streams: Black Creek; Cheryl Sink; Fisher Creek; Jump Creek; Lost Creek; Sullivan Sink; Mill Creek
  - Sinking lakes: Bradford Brook Chain of Lakes (Lake Cascade); Lake Iamonia (Iamonia Sink); Lake Jackson (Porter Hole Sink); Lake Lafayette (Fallschase Sink); Lake Miccosukee (Miccosukee Sink); and Lake Munson (Ames Sink).

Rainfall Data



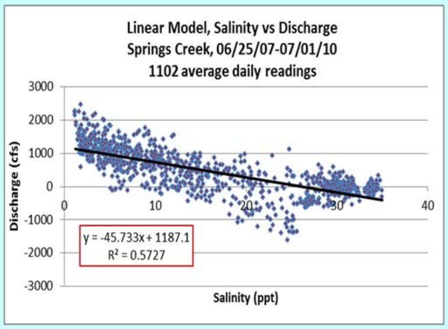
- Because of a gap in the Wakulla Springs rainfall data beginning 7/8/16, we used the Tallahassee data combined with the Wakulla Springs data to represent rainfall in these analyses, occasionally examining each individually where we suspect one or the other may be more representative of more localized precipitation, e.g. the Wakulla Springs data for the Spring Creek springshed and the Tallahassee data for the sinking stream drainage area.
- As shown in this figure, The Wakulla Springs and Tallahassee rainfall patterns are similar but rainfall amounts differed, sometimes substantially, on some occasions

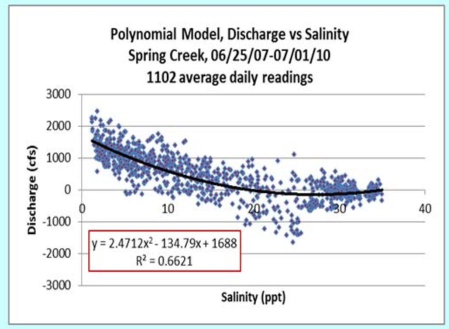
Discharge Patterns: Wakulla Spring and Spring Creek

- Wakulla Spring (USGS @ Shadeville Road bridge)
  - range: 528 to 1,650 cfs
  - average: 875 cfs
- Spring Creek (specific conductance proxy)
  - range: -150 to 1,674 cfs
  - average: 446 cfs

- We used discharge data from the USGS gauges at Lost Creek, Fisher Creek, Black Creek, Wakulla River at Shadeville Road bridge, and Spring Creek.
- Because of prolonged gaps and inaccuracies in the Spring Creek discharge data we constructed two models to estimate flow based on salinity/specific conductance
- We estimated both linear and polynomial regression models based on over 1,102 daily average readings of salinity and discharge from the USGS gauge from 06/25/07 to 07/01/10
- The polynomial model provided a better fit based on the R2 coefficient of determination **[regression fits on hidden slide that follows]**.
- The Spring Creek springs at times ceased to flow; average daily flow during the study period based on our specific conductance proxy was 446 cfs at the boat dock.
- Wakulla Springs averaged almost twice as much at 875 cfs

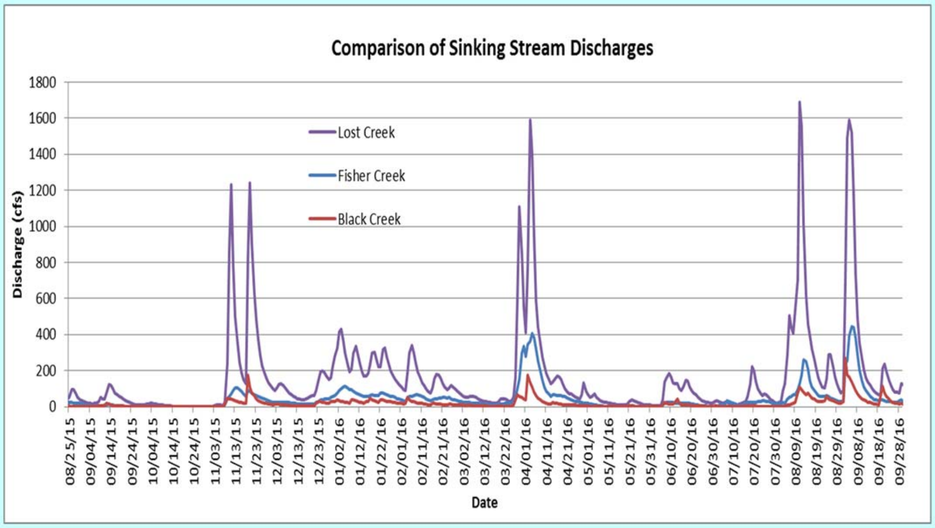
Spring Creek Discharge Model





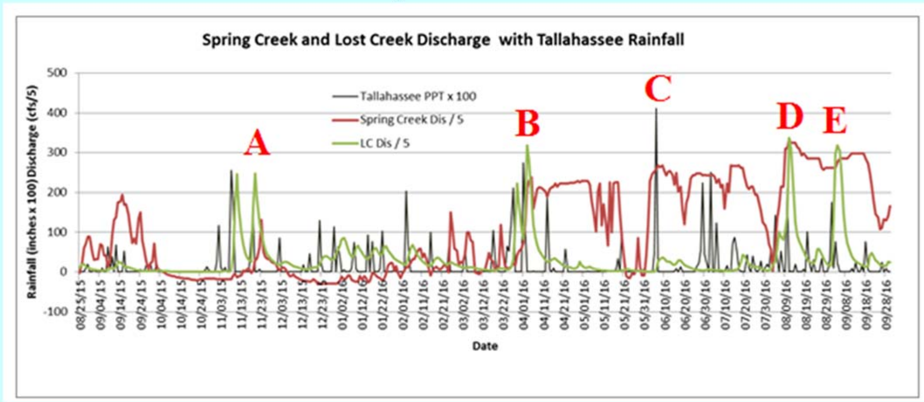
- The flow data has been modified using the theory behind the "Fraction of Salinity Model' of Thomann and Mueller (1987).
- R2 for linear model = 0.57
- R2 for polynomial model = 0.66

Sinking Stream Discharge Patterns



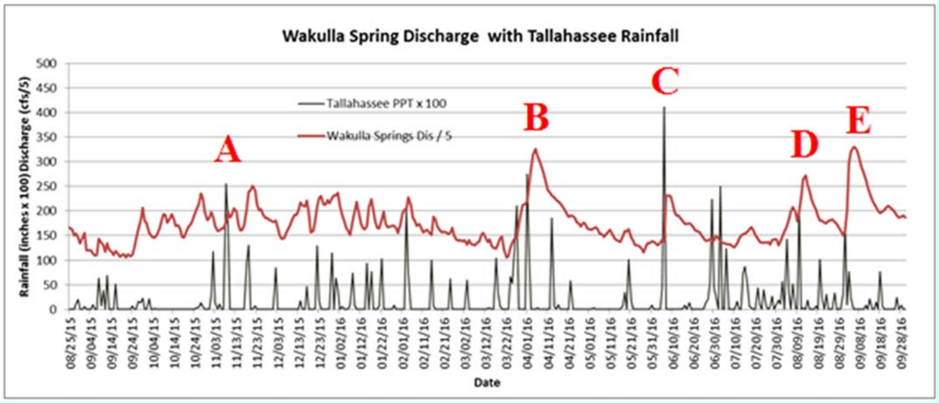
- Sinking streams flowed intermittently with modest average daily flows
- Lost Creek predominated:
    - Black Creek - 18 cfs)
    - Fisher Creek - 43 cfs
    - Lost Creek - 158 cfs

Spring Creek Springs Flow Dynamics

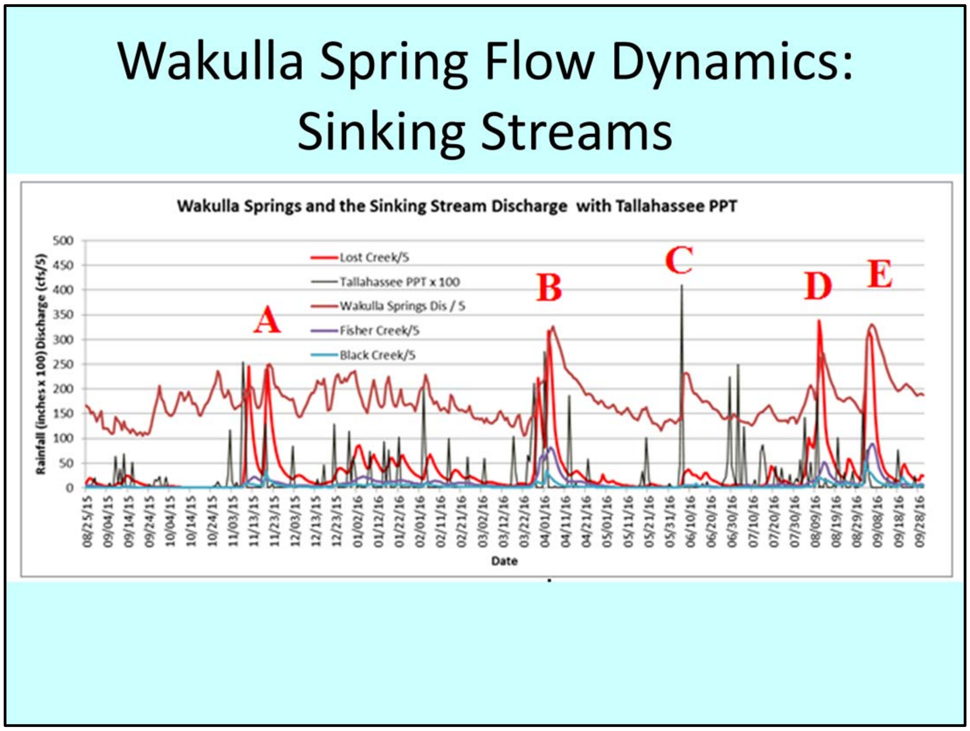


- Davis and Verdi (2014) explain the periodic cessation and sometimes negative discharge of the Spring Creek springs as the result of prolonged periods of little or no rainfall coupled with higher mean sea level.
- Under these circumstances, the hydraulic head differential between the Spring Creek water table and sea level is sometimes too little to maintain flow from the Spring Creek springs.
- The flow dynamics we observed during this study are consistent with those explanations.
- As shown in this figure, local and regional rainfall and associated discharges from Lost Creek into its sink correspond well with discharges from the Spring Creek springs.
- The Spring Creek springs discharge peaks at nodes A, B, D, and E follow shortly after rain events that also are associated with peak discharges from Lost Creek. The restoration of flow at Spring Creek at node C coincides with a rainfall event measured at the Tallahassee Airport for which there is a considerably smaller increase in discharge from Lost Creek probably of prolonged low rainfall.

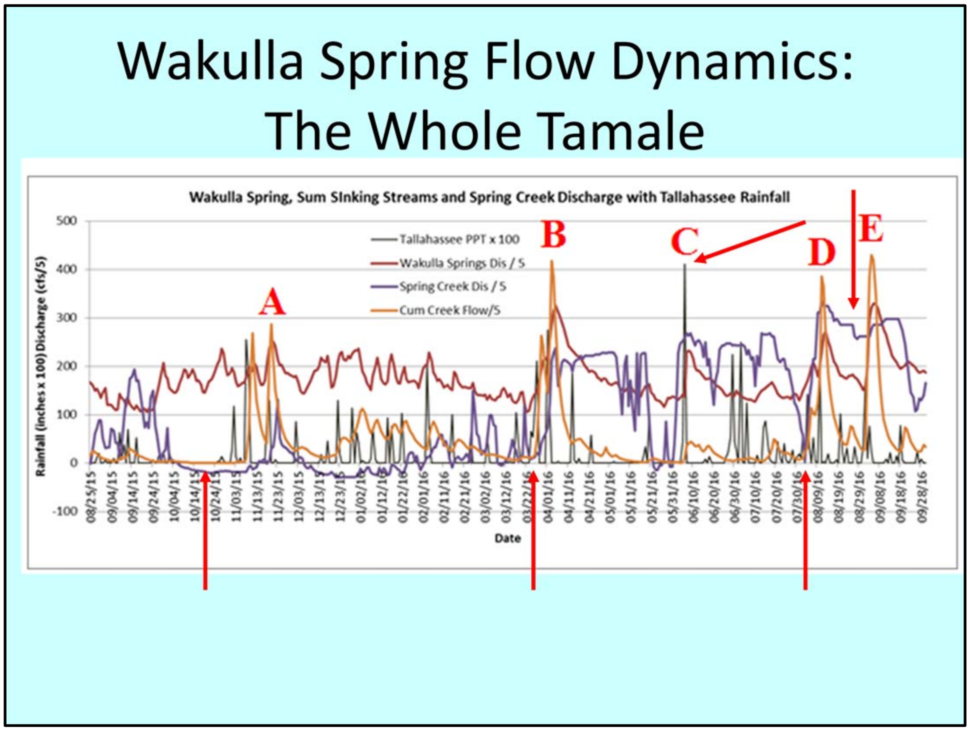
Wakulla Spring Flow Dynamics: Rainfall



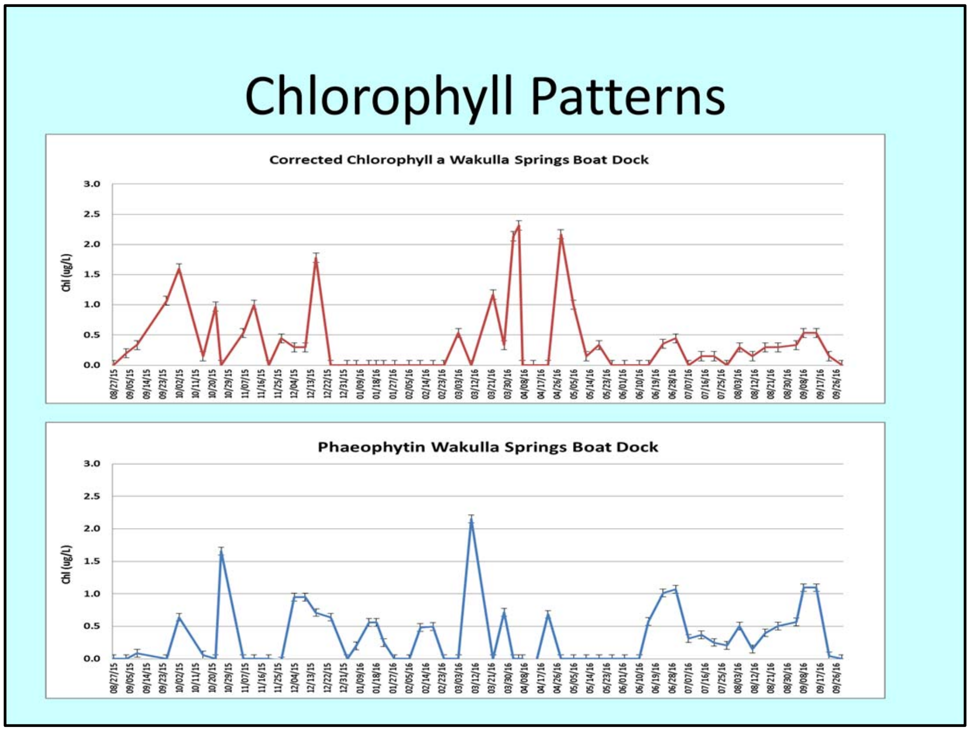
- Minor rainfall events of one inch or less have little apparent effect on Wakulla Spring discharge, but larger rainfall events are associated with discharge peaks
- Each of the major discharge peaks (nodes B-E) is associated with preceding rainfall patterns.
- Peaks at nodes B, D, and E each appear to be associated with the cumulative effects of several rain events.



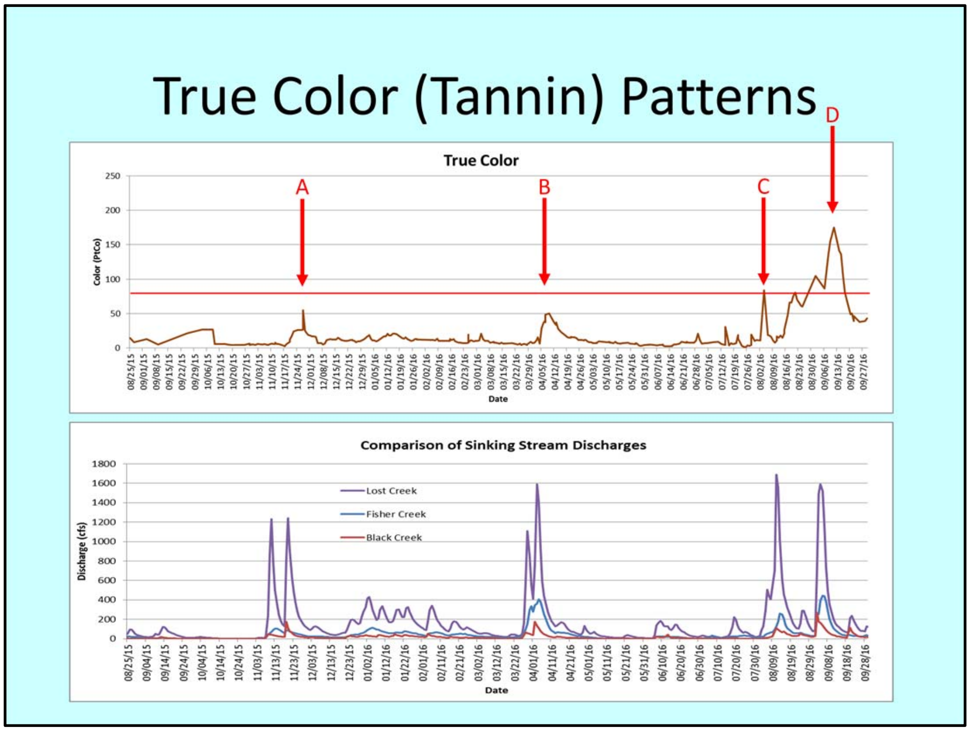
- As shown in this figure, the impacts of the sinking streams on spring discharge, while sometimes pronounced, are generally short-lived. The dominant determinant of spring discharge is the base flow from the aquifer.
- With the exception of spring discharge peak C, the major peaks are associated with increases in flow from all three of the sinking streams.
- However, we cannot ascertain easily from these figures if Lost Creek discharges are flowing north to Wakulla Spring or flowing south to Spring Creek



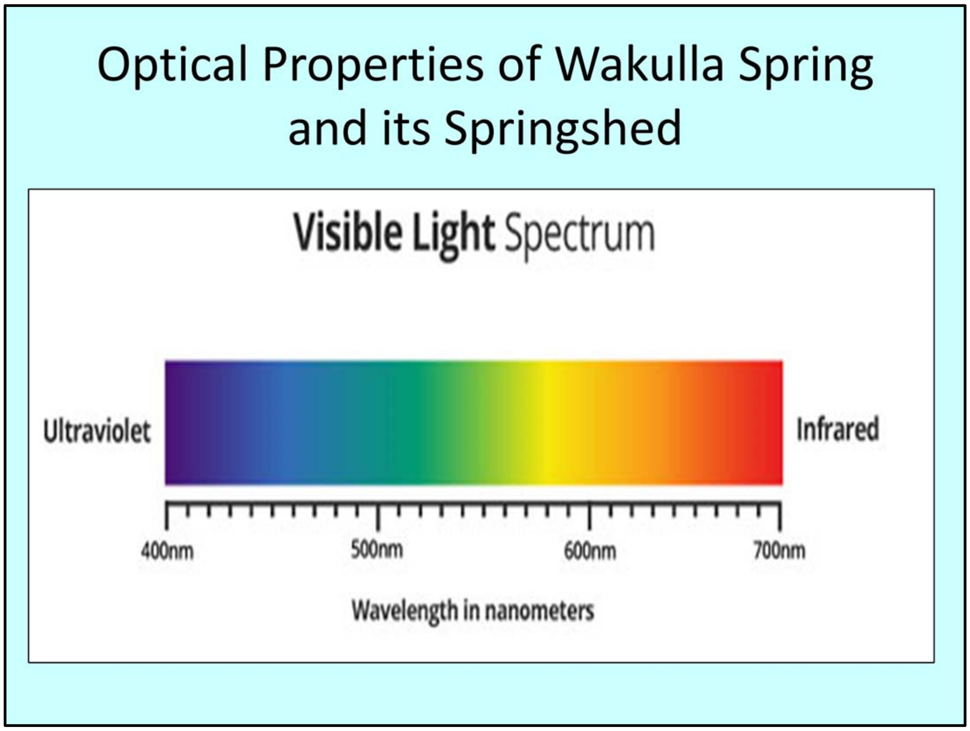
- This figure, which displays Wakulla Springs discharge (dark red) with rainfall (black) plus discharges from the Sinking Streams (orange) and Spring Creek (purple), offers some insight. **[Need to fix this graph. It displays cumulative sinking stream flows rather than just Lost Creek.]**
- This shows that Spring Creek was not flowing prior to Wakulla Spring discharge peak A **[click]**, so Lost Creek flows should have been a major contributor to flow at Wakulla. However, the impact of the three sinking streams is relatively modest and short-lived, perhaps because of the relatively low rainfall prior to the rainfall event the triggered peak A.
- Very low Spring Creek discharges and high sinking stream flows are associated with Wakulla Spring discharge peaks B and D **[click]**
- However, Spring Creek was still flowing at a high level prior to and throughout the time of Wakulla Spring discharge peak E **[click]**, indicating that Lost Creek flow would likely not have contributed to the discharge event at Wakulla Spring even though total sinking stream flow was very high at that time.
- Wakulla Spring discharge peak C **[click]** appears to have been drive primarily by rainfall – the largest rainfall event of the study period at slightly over 4 inches



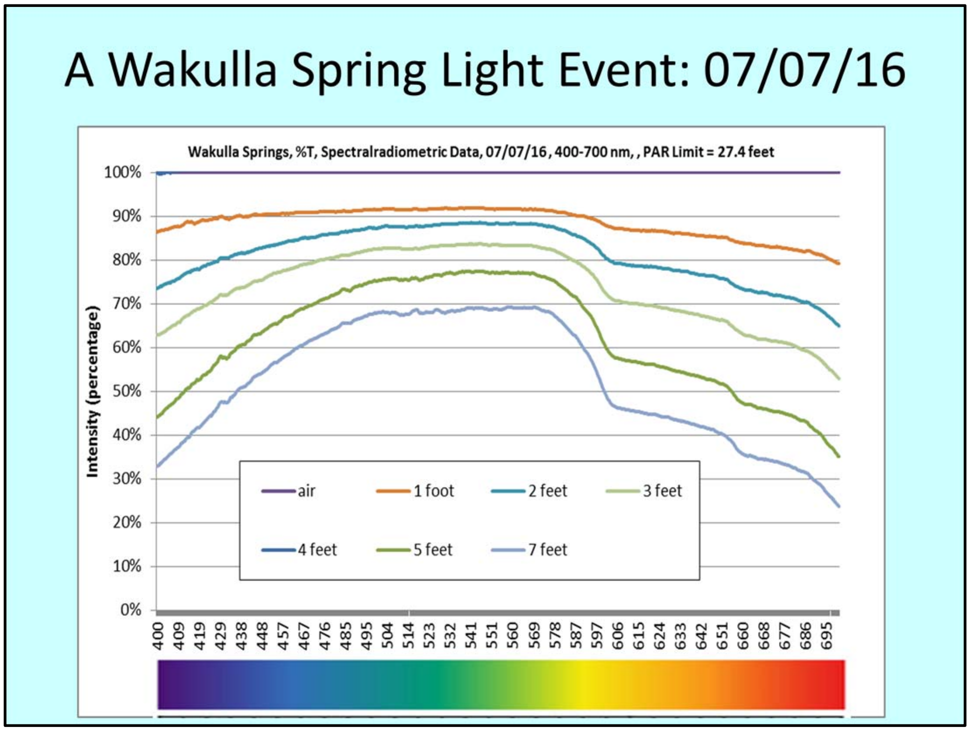
- These figures show that corrected chlorophyll a and phaeophytin levels at Wakulla Spring show little correlation with each other, with the exception of the last few months of the data series when they parallel each other fairly closely
- There are no apparent relationships between either of these chlorophyll measures and rainfall, sinking stream discharges, or Spring Creek flow patterns.
- **Should we look at Wakulla Spring nitrate levels and/or WS discharge? Nitrate levels might be a proxy for base flow**



- Three of the true color (tannin) peaks occur shortly after peaks in sinking stream flows **[click]**
- Spring Creek was not flowing at the time of the two Lost Creek discharge peaks that precede true color peak A, so tannins likely came from all three sinking streams
- Prior to true color peak B, the first Lost Creek discharge peak occurred when Spring Creek was not flowing; the second occurred after Spring Creek commenced to discharge
- True color peak C also occurred immediately after a cessation of flow at Spring Creek at the front end of an increase in discharge from Lost Creek and prior to increased flow in the other two sinking streams
- True color peak D has three high points and is associated with two peaks in flow by all three sinking streams. However, these occur when Spring Creek was flowing vigorously, so it is likely that the tannins originated primarily from Black and Fisher Creeks on this occasion
- True color and chlorophylls are largely independent except during the latter few months of the sampling period when they seem to all three run in parallel. **WHY?**

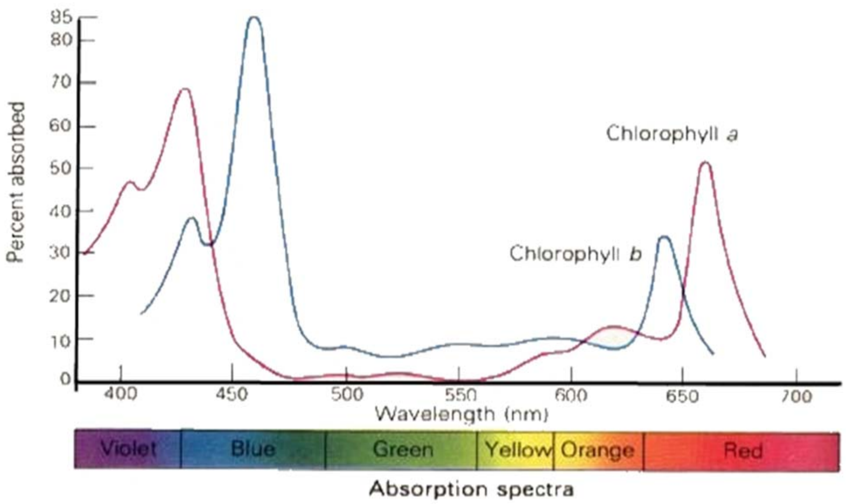


- Light is the most critical parameter in determining the diversity and abundance of aquatic biological communities.
- Plants need almost the full spectrum of visible light to photosynthesize. This so-called Photosynthetically Active Radiation (PAR) encompasses the spectral range (wave band) of solar radiation from 400 to 700 nanometers which is the same as the light range visible to humans
- We examined the light spectrum transmitted through the water column at Wakulla Spring using spectral radiometric (spec rad) analysis of unfiltered water in the field to define “optical fingerprints” of light conditions at the spring under both “dark” and “light” water conditions.
    - “Dark” conditions comprise those when significant amounts of tannins are in the water and the color appears reddish brown.
    - “Light” conditions are those when tannins are not noticeably present.
- We also developed optical fingerprints for some of the karst lakes and streams that discharge water into the Upper Floridan Aquifer within the Wakulla Springshed. Here we present several examples.

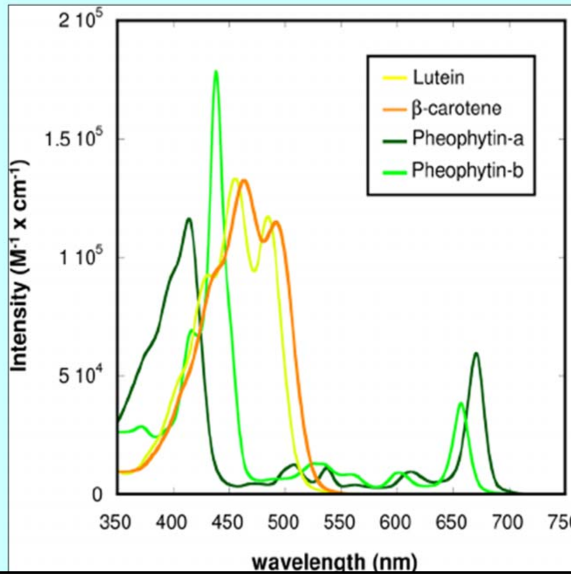


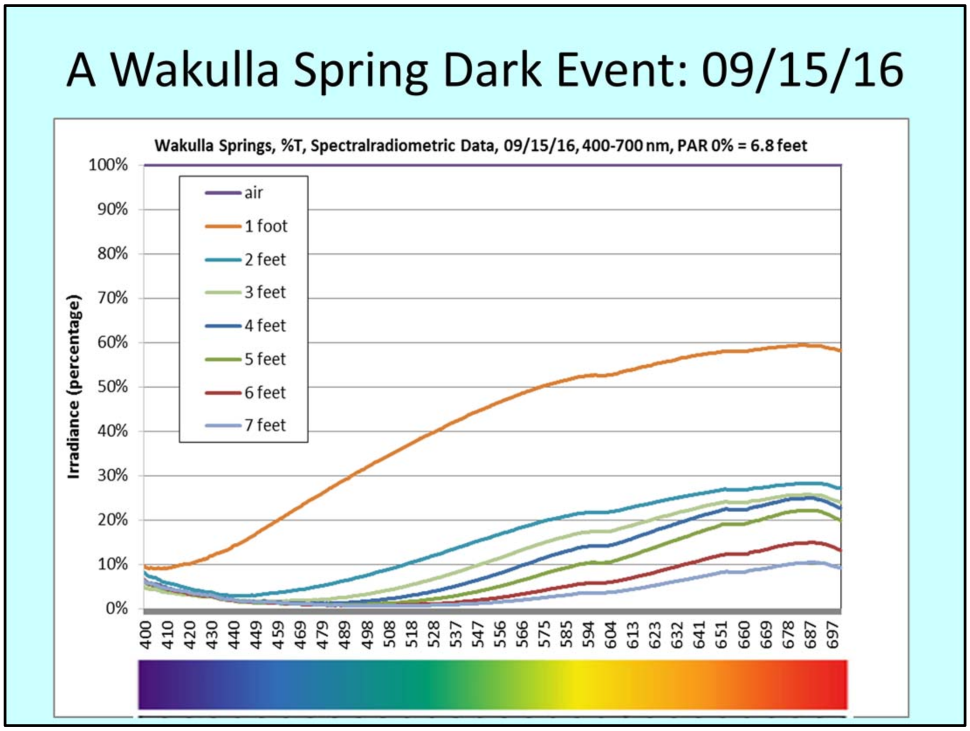
- This figure presents the optical fingerprint of a light event at Wakulla Springs on July 7, 2016.
- Secchi visibility depth was 63 feet – one of the "clearest" conditions during the study
- In this figure, visible light intensity has been normalized to present percent transmittance relative to light intensity measured at the surface.
- Both the shortest wavelengths (< 440 nm) and the longer wavelengths (>570 nm) were being absorbed hence lower transmittance values
- This absorbance pattern is indicative of chlorophylls
- The greatest transmittance occurred in the middle (about 480-570 nm, i.e. greens and yellows). So the apparent water color would have been greenish.

Light Absorbance Spectra of Chlorophyll a and b

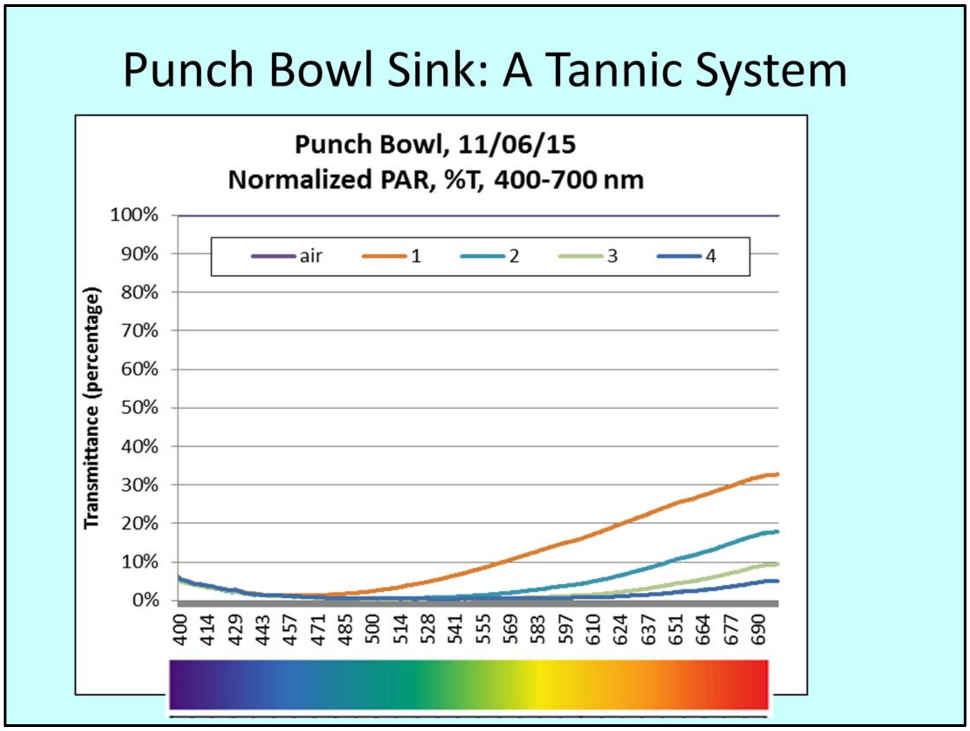


Light Absorbance Spectra of Phaeophytin a and b

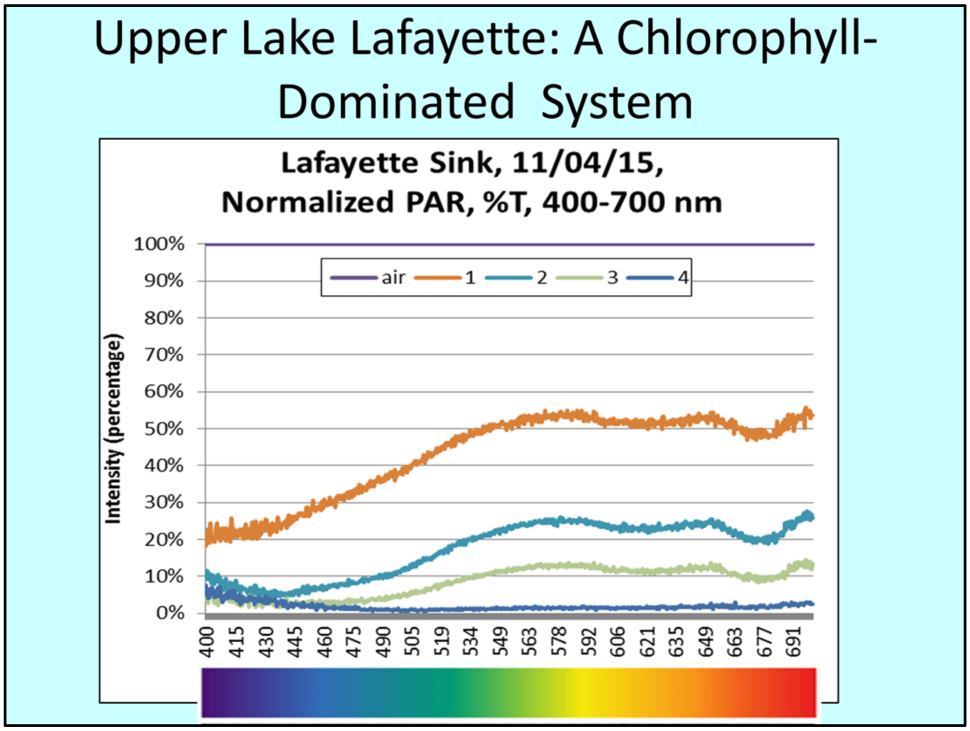




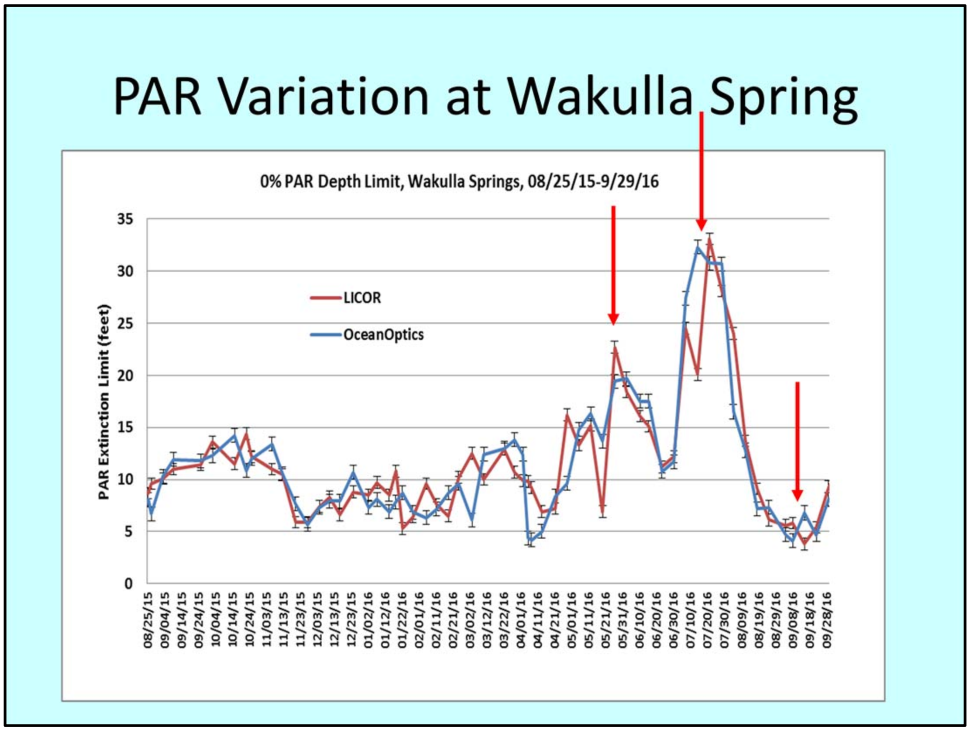
- This figure presents the optical fingerprint of a dark event at Wakulla Springs on September 15, 2016.
- Secchi visibility depth was 5.5 feet – one of the “darkest” conditions during the study
- The entire spectrum is shifted to the right by the tannic condition in the dark event with the peak intensity moving from about 520 nm in the light event to about 680 nm.
- The tannins in the Spring water absorb highly in the blues and greens, so transmittance is low in the short wavelengths of the PAR.
- The longer wavelength yellows and reds (580-700 nm) are typically transmitted giving the tannic water its characteristic brown or reddish brown apparent color.
- Here there is some overlap into the greens (500-560 nm), possibly because of the presence of both tannins and chlorophyll.



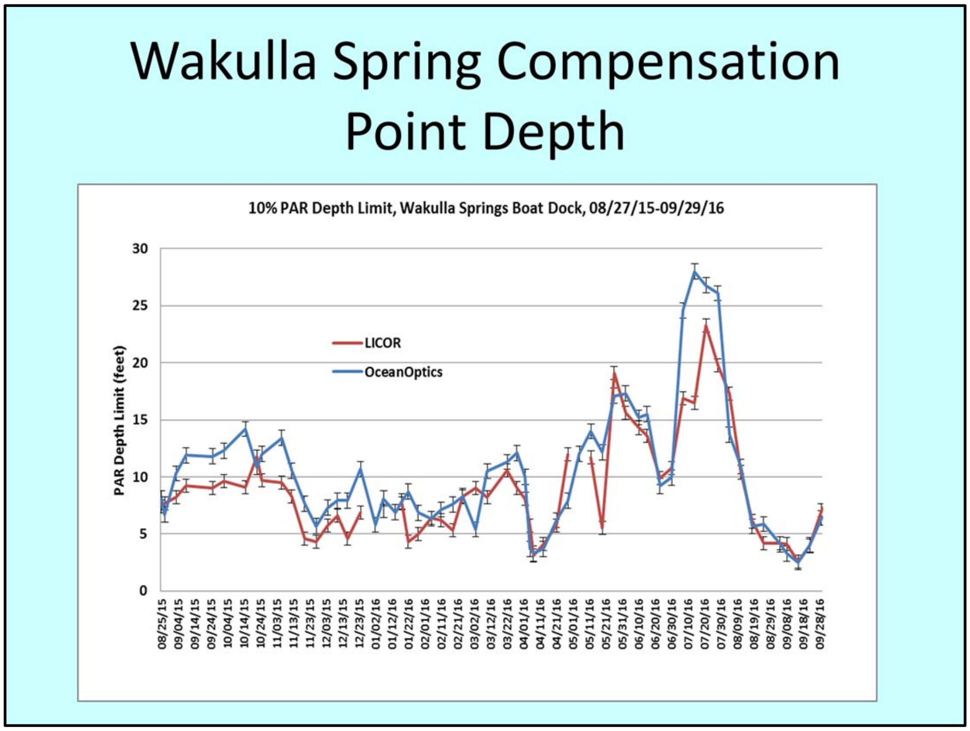
- This figure presents the optical fingerprint of a purely tannic system – Punch Bowl Sink - a dark water “karst window” sink that is directly connected to the aquifer and has very high levels of tannins from open conduits connected to the underground flow from Lost Creek.
- The color peak is again at approximately 680 nm



- This figure presents the optical fingerprint of a lake dominated by chlorophyll from microalgae blooms – Upper Lake Lafayette
- Transmittance is low below 500 nm and there is a distinct dip at about 664nm.
- These patterns are consistent with the typical absorbance patterns of chlorophyll a and phaeophytin.
- Bu high transmittance in the long wavelengths too suggests some tannins as well.
- Apparent color would be a mix of green and brown

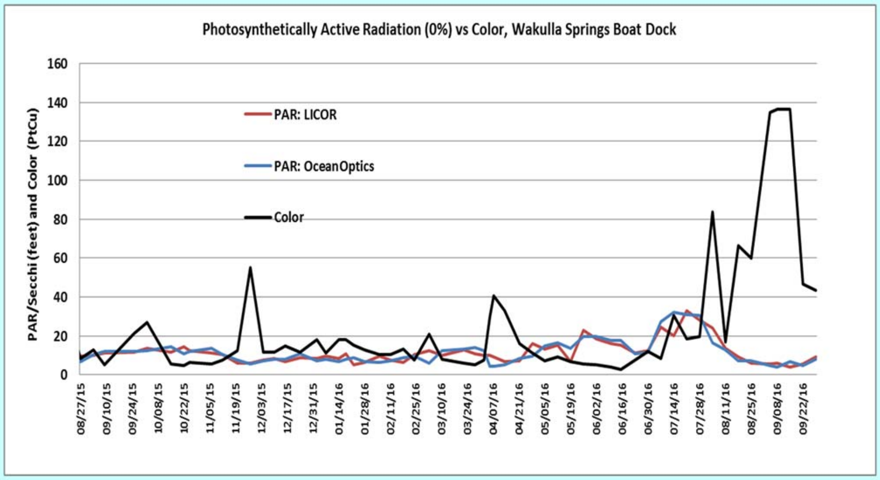


- We defined the depth of the photic zone, calculated from an extinction coefficient using the spectrophotometric data, as the depth at which PAR falls to 0% transmittance. This quantifies the maximum depth of the photic zone, where all photosynthetic productivity has its inception.
- We calculated this weekly, based on in situ measurements taken with two devices: a LICOR photometric cell and an Ocean Optics underwater, integrating spectrophotometer (OOS).
- Results from the two devices were strongly correlated (R2 = 0.73)
- The figure depicts two clear events towards the end of the project, May 30 **[click]**, and another on July 10, 2016 **[click]**.
- In May it was clear enough to run the glass bottom boats for the first time since 2014; PAR depth was 20-22 feet
- In July PAR light penetration depth was about 33 feet.
- This period of exceptional water clarity was caused by a cessation of flow from the sinking creeks and good flow at Spring Creek and a time period without rainfall
- **[click]** Then in late September the PAR light penetration depth decreased to about 3 feet **[6.8 ft is what you report earlier]**.

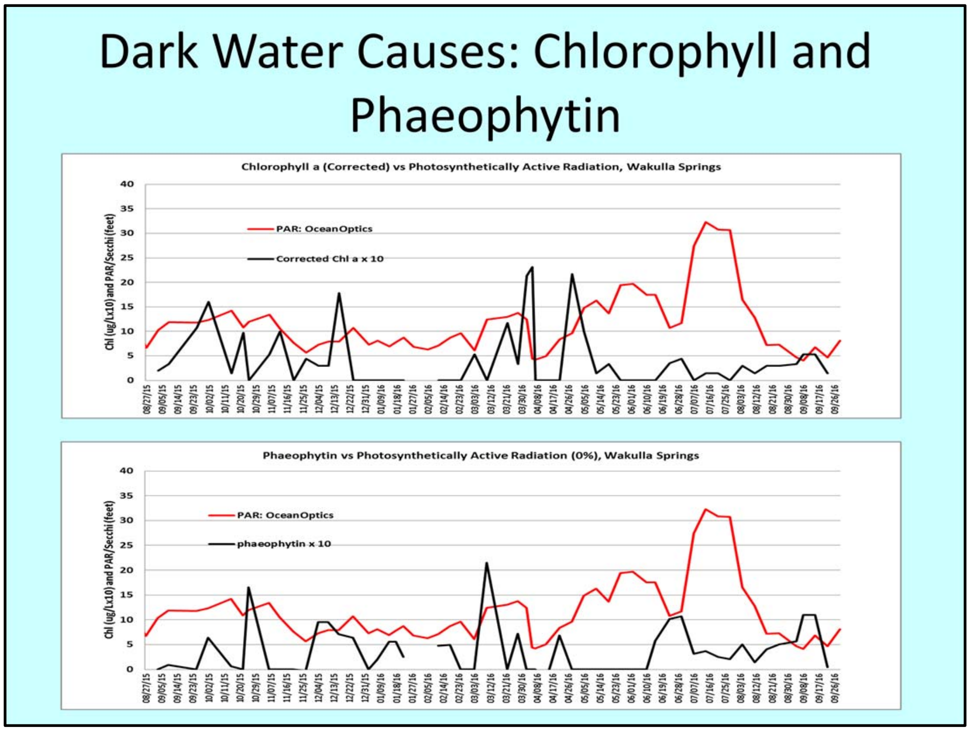


- This figure displays the 10% PAR depth limit for the study period.
- This is the depth at which the two dominant submerged aquatic grass species in the spring bowl and Upper Wakulla River, *Vallisneria americana* and *Sagittaria kurziana*, receive just enough PAR to produce by photosynthesis the amount of sugar needed to offset the amount consumed by respiration.
- Note that the average appears to be 10 feet or so, suggesting that survival of the native aquatic grasses may be limited at greater depths

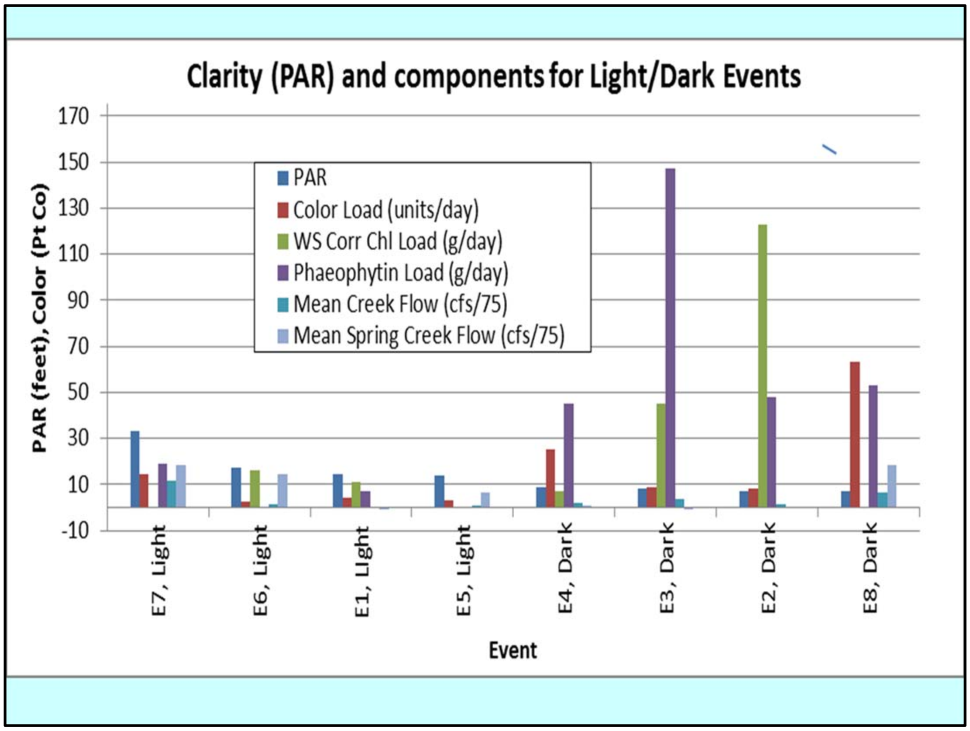
Dark Water Causes: Tannins



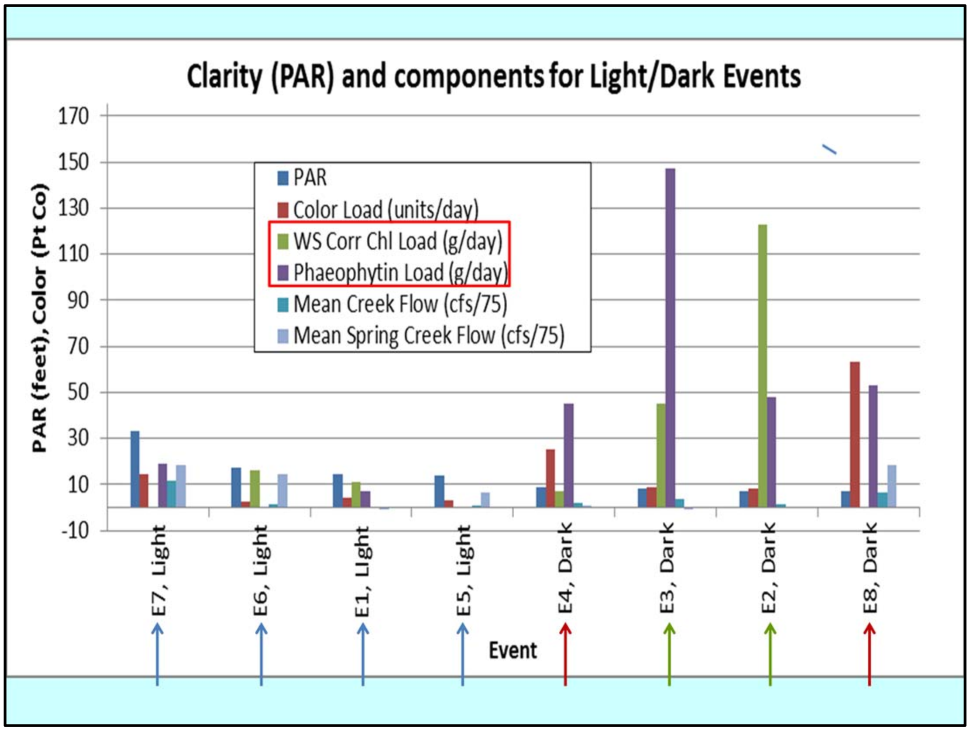
- The two primary proximate causes of “dark” water conditions that result in low PAR extinction depths should be the two sources of color: (a) tannins (measured as true color) and (b) chlorophyll and/or phaeophytin
- This figure reveals that the PAR depth limit was generally highest when true color was low, but the PAR depth limit does not directly reflect true color levels in all instances.
- The linear regression coefficient of determination (R2) of PAR depth limit versus true color is statistically insignificant, suggesting that tannins acting alone are not a significant determinant of PAR depth limit in Wakulla Springs



- Graphs of PAR depth limit with corrected chlorophyll and with phaeophytin show that our exceptionally clear episodes, the two clear events towards the end of the project, May 30, and July 10, 2016, also occurred during low concentrations of corrected chlorophyll a in Wakulla Springs.
- Phaeophytin patterns differ but also are generally lowest when PAR depth is greatest.
- As with true color, neither corrected chlorophyll nor phaeophytin alone is a statistically significant correlate of PAR depth.
- This suggests that the optical properties of Wakulla Springs water are more complex than previously thought and not due to any one cause but rather to the combined effects of chlorophylls and tannins in the water column.
- **We ought to do a multiple regression with all three color sources and PAR plus a Lost-Creek-Spring Creek interaction term SCF*LCD where**
    - **SCF = 0 if SCD LE 0, ELSE SCI = 1**
    - **SCF = Spring Creek Flowing/Not Flowing**
    - **SCD = Spring Creek discharge**
    - **LCD = Lost Creek discharge**



- This conclusion is further demonstrated by this figure which depicts findings from the four "light events" and four "dark events" analyzed during Phase I of this project
- Shown here are PAR depth, total loads in grams per day of the three color sources, as well as mean flow in the sinking streams/creeks and at Spring Creek
    - Dark blue (far left) = PAR depth
    - Dark red = true color (tannin load)
    - Green = corrected chlorophyll a load
    - Purple = phaeophytin load
    - Light blue = mean creek flow **[mean of what?]**
    - Gray-blue = mean Spring Creek flow **[mean of what?]**
- **GO TO NEXT SLIDE**



- During the four "light events" on the left
  - Corrected chlorophyll a and phaeophytins – the green and purple bars **[click] -** are low or absent
  - Some tannins – dark red bars - are present in each, but creek flows are minimal (except in E7)
  - Spring Creek is flowing in three light events (not E1)
  - E5 stands out as having no chlorophyll a or phaeophytin load, yet PAR depth is only slightly > 10 ft
  - E7 stands out as having greatest PAR depth (>30 ft), yet has highest loads of tannins and phaeophytin (but no chlorophyll a) of the four light events
- During "dark events" on the right
  - Phaeophytins (purple bars) are quite a bit higher during all four events
  - Corrected chlorophyll a (green bars) also is much higher in two of those events (E2 and E3), adding to the effects of the phaeophytins **[click]**
  - During the other two dark events, tannins are higher than during the light events and add to the effects of the phaeophytins **[click]**
  - Spring Creek flow is LE zero in three of four dark events (not E8)

Summary

- Our analyses documented complex flow dynamics involving Lost Creek, Spring Creek, and Wakulla Spring consistent with the findings of Davis and Verdi (2014) and Dyer (year)
- PAR depth is being affected by all three pigments: tannins (true color), chlorophyll a, and phaeophytins

Summary

- "Dark" water conditions (with PAR depths < 10 ft)
  - Some combination of tannins (true color), chlorophyll a, and/or phaeophytins
  - Spring Creek discharge LE 0 in 3 of 4 events
- "Light" water conditions (PAR depth > 10 ft)
  - Low levels of tannins (true color) present during each
  - Low levels of chlorophyll a and/or phaeophytins in 3 of 4 events
  - Spring Creek flowing in 3 of 4 events

Phase II

- Dye tracer tests: Upper Lake Lafayette and Lake Jackson
- Algae identification during lake algae bloom season
- Dissolved Organic Matter molecular analyses by Rob Spencer and Dave Podgorski at the Mag Lab – Might best be done during low algae bloom light conditions when presumably dominant color cause is phaeophytins