Chaotic, Non-Linear Dynamics of Water Chemistry in a Florida Freshwater Stream

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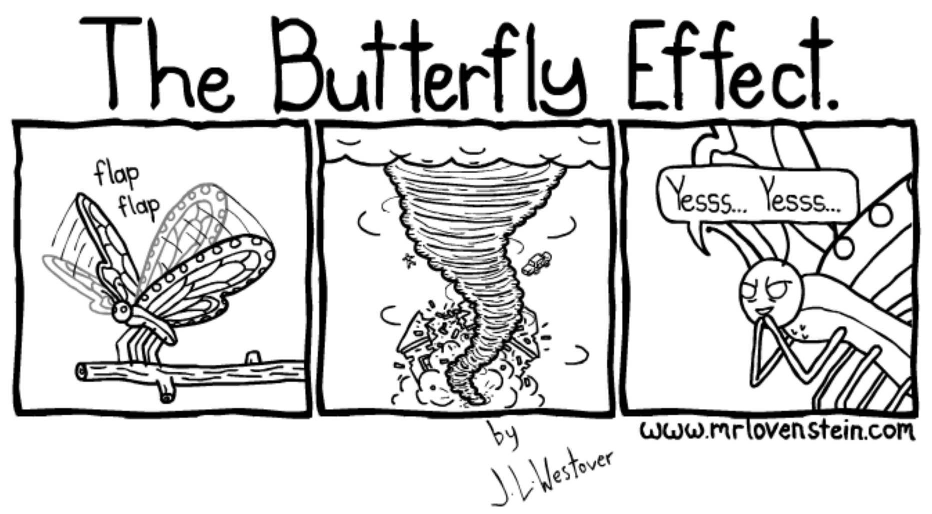
Introduction

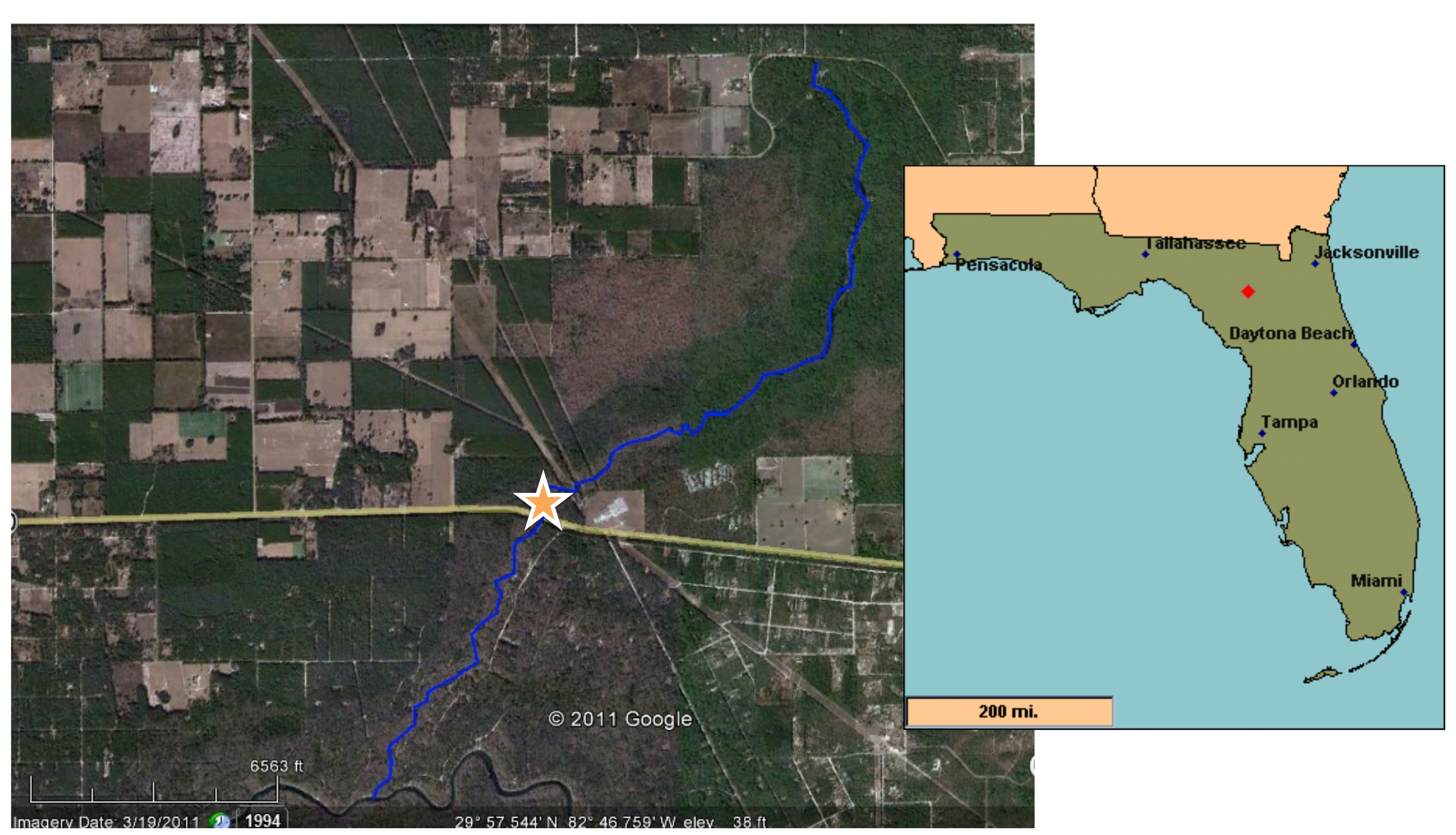
- Chaotic systems are non-linear, and exhibit strong sensitivity to initial conditions. While inherently deterministic, modeling in chaotic systems leads to increasing divergence from expectations over time.
- Chaotic systems also have a strange attractor (fractal correlation dimension)
- Florida Springs are increasingly being understood as complex systems.
- Here we investigate metrics of river metabolism for chaotic behavior and reconstruct the data using a single spectrum analysis.



Chaos Theory is most commonly understood as the butterfly effect, where small changes in a complex system can lead to large and unexpected results.

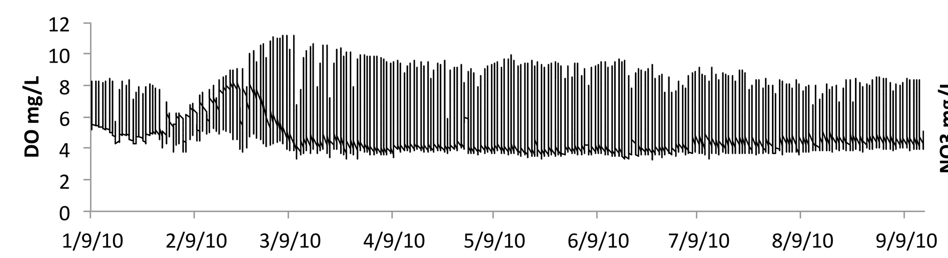
Field Sampling

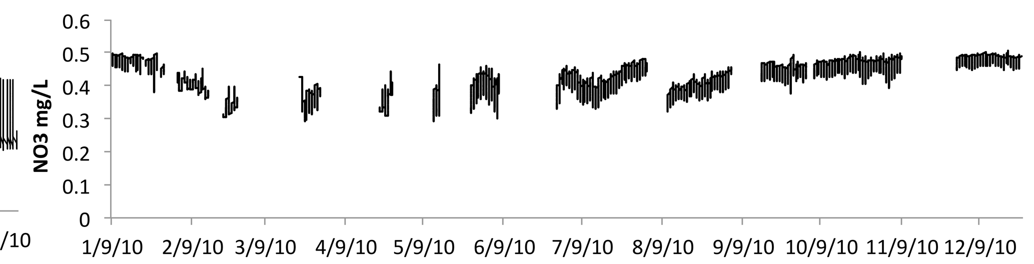
- Sensor arrays were deployed in the Ichetucknee River just above US 27 in 2010.
- NO_3^- was measured using an In Situ Ultraviolet Sensor (ISUS) version 3 at 15 min intervals.
- Dissolved oxygen (DO) was measured hourly by an YSI 600XLM sonde.
- The longest data sets likely to have sufficient oscillations (diel cycle) to provide accurate results were chosen (2 for DO, 13 for NO_3^-).



Itchetucknee Spring and Run in Columbia County, FL. The location of the sensor deployment is starred. Image is from Google Earth.

Methods





Chaos

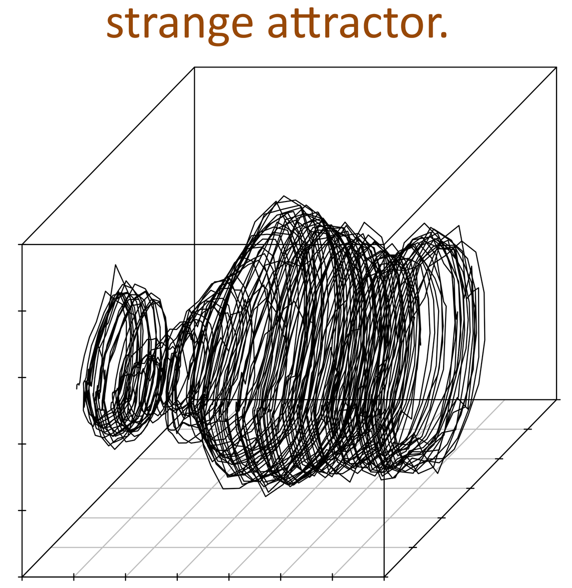
The Lyapunov Exponent (L.E.) is a measure of behavior near the edge value of equilibrium and is one approach to show deterministic chaos. This exponent was calculated and then compared to 50 surrogate data sets generated by both a noisy limit cycle and Theiler's amplitude adjusted fourier transformation to ensure noise did not generate a falsely positive L.E. We then used an embedding delay to reconstruct the strange attractor, and similarly compared the fractal dimension to surrogate data sets.

Single Spectrum Analysis

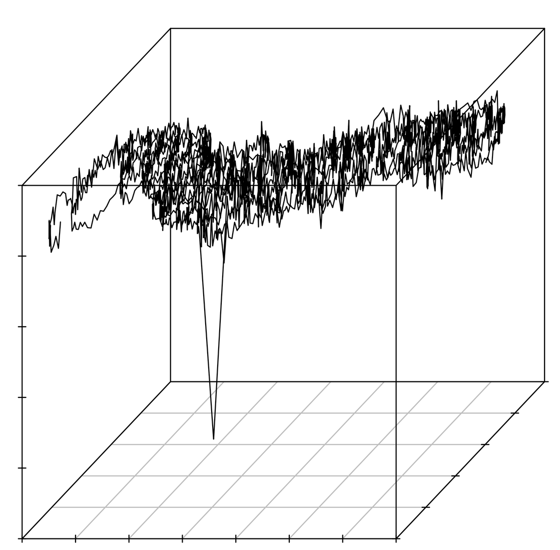
SSA is a technique to extract trends and cycles from data sets using an embedding delay. To ensure the strange attractor was not not caused by red noise, a Monte-Carlo SSA technique was employed. Red noise is a decaying autocorrelation structure in the residuals and is found in some biological systems.

Chaos and Fractal Dimension

Examples of the reconstructed strange attractor.



DO mg/L
1/9-5/27/2010



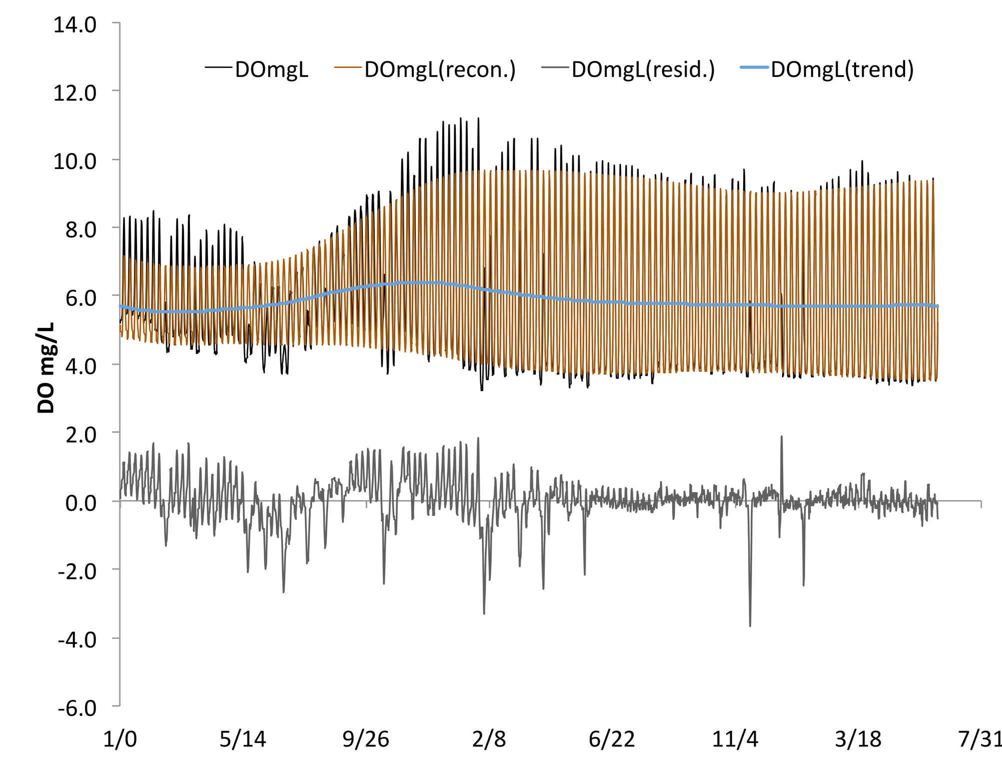
Nitrate
6/29-8/3/2010

	Time Series	Surrogate (mean)	p-values
DO mg/L 1/9 - 5/27/2010			
Correlation Dimension	2.98	2.19	0.00
Lyapunov Exponent	1.77	3.02	0.00
DO mg/L 5/27 – 9/14/2010			
Correlation Dimension	1.90	2.07	0.00
Lyapunov Exponent	4.25	2.85	0.00
NO_3^- 6/29 - 8/3/2010			
Correlation Dimension	0.92	2.02	0.00
Lyapunov Exponent	6.45	3.52	0.00
NO_3^- 10/6 - 11/9/2010			
Correlation Dimension	1.73	1.97	0.00
Lyapunov Exponent	3.28	3.35	0.89

Examples of the chaos measures for some of the data sets.

- All of the DO and SpC (not shown) data sets exhibited a significant Lyapunov Exponent and correlation dimension.
- Comparatively, only about half the nitrate data sets had both significant chaos and correlation dimension, although the L. E. was always positive (ranged 1.93-6.45) with a fractal correlation dimension (ranged 0.93-2.73).

SSA Reconstruction

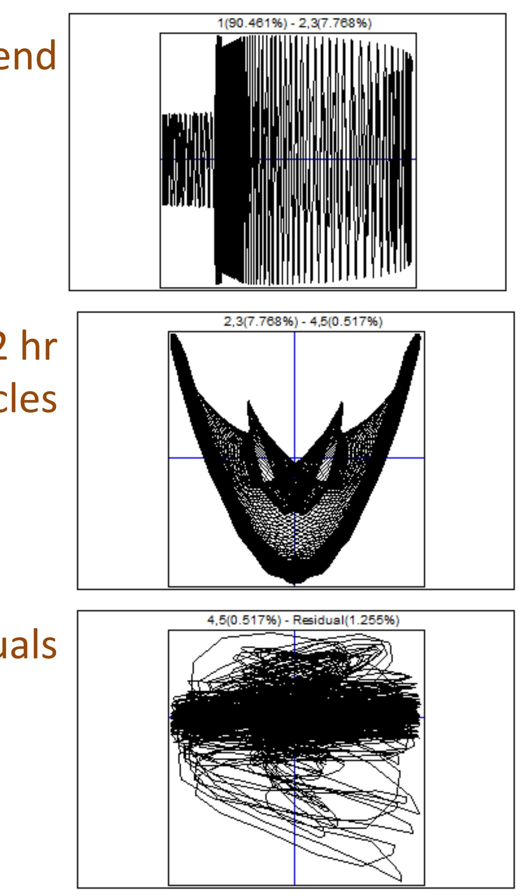


Reconstructions: Phase Space

trend

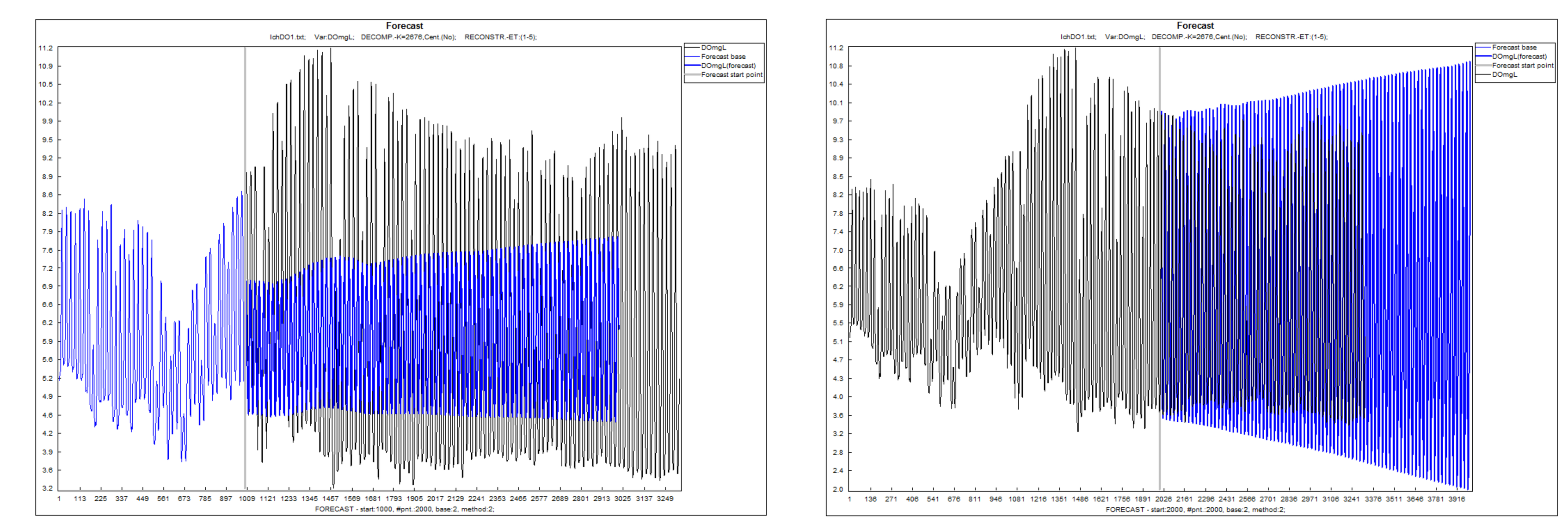
24 & 12 hr cycles

residuals



SSA Reconstruction is shown for one of the data sets (DO; 1-9 - 5/27). All of the data sets showed both a 24 &12 hr cycle that was not created by red noise. The reconstructions were all good fits of the data (explaining 89-96% of the variance). The difficulty in modeling chaotic systems is demonstrated by forecasting, where either 1,000 or 2,000 data points were used as the base for the forecast (below).

Forecasting:
Why sensitivity to initial conditions matters!



Conclusions

- Results indicate:
    - Strongly oscillatory components with some trend, where red noise is not a significant component,
    - A well defined attractor for all three metabolic constituents (NO_3^-, DO, and SpC), and
    - Fractal and chaotic nature to the attractors.
- Chaos in metabolism may be the result of weather influence– induced by chaos in cloud cover and precipitation patterns, etc.
- The unexpected 12-hr cycle may be caused by upstream influences on local conditions.
- Spring metabolism is non-stationary, and these results provide the skeleton framework for modeling.

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