Generalized Additive Model (GAM) Development Briefing:
Application to Tidal Water Quality

Water Quality GIT

Sept. 14, 2015

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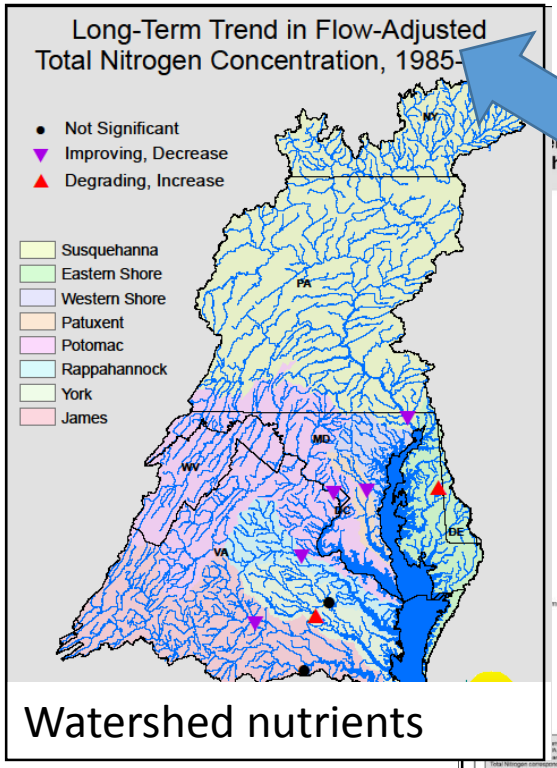
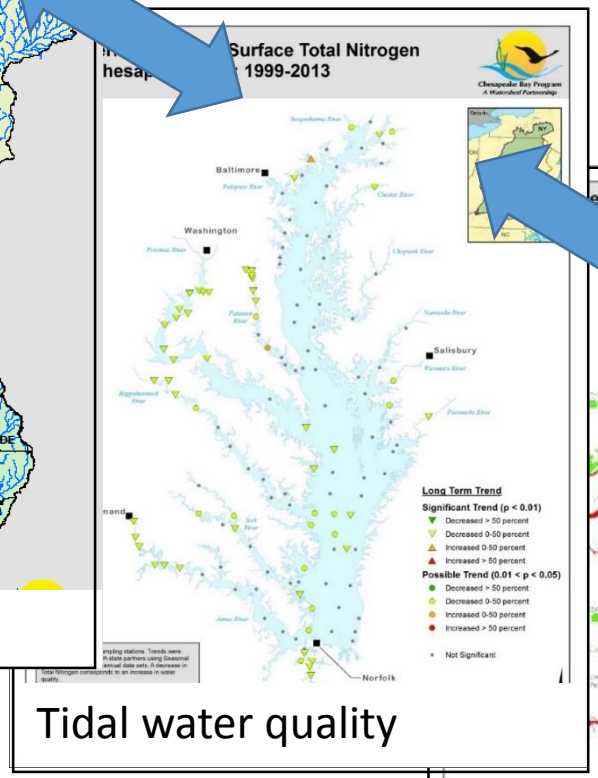
Chesapeake Bay Program

Science. Restoration. Partnership.

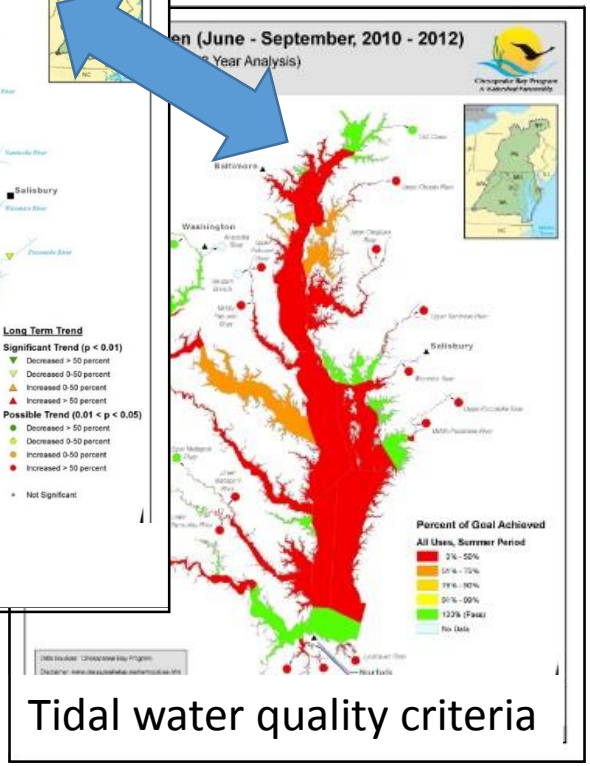
Using Monitoring Data To Measure Progress and Explain Change



Watershed nutrients



Tidal water quality



Tidal water quality criteria

Linked efforts underway to:

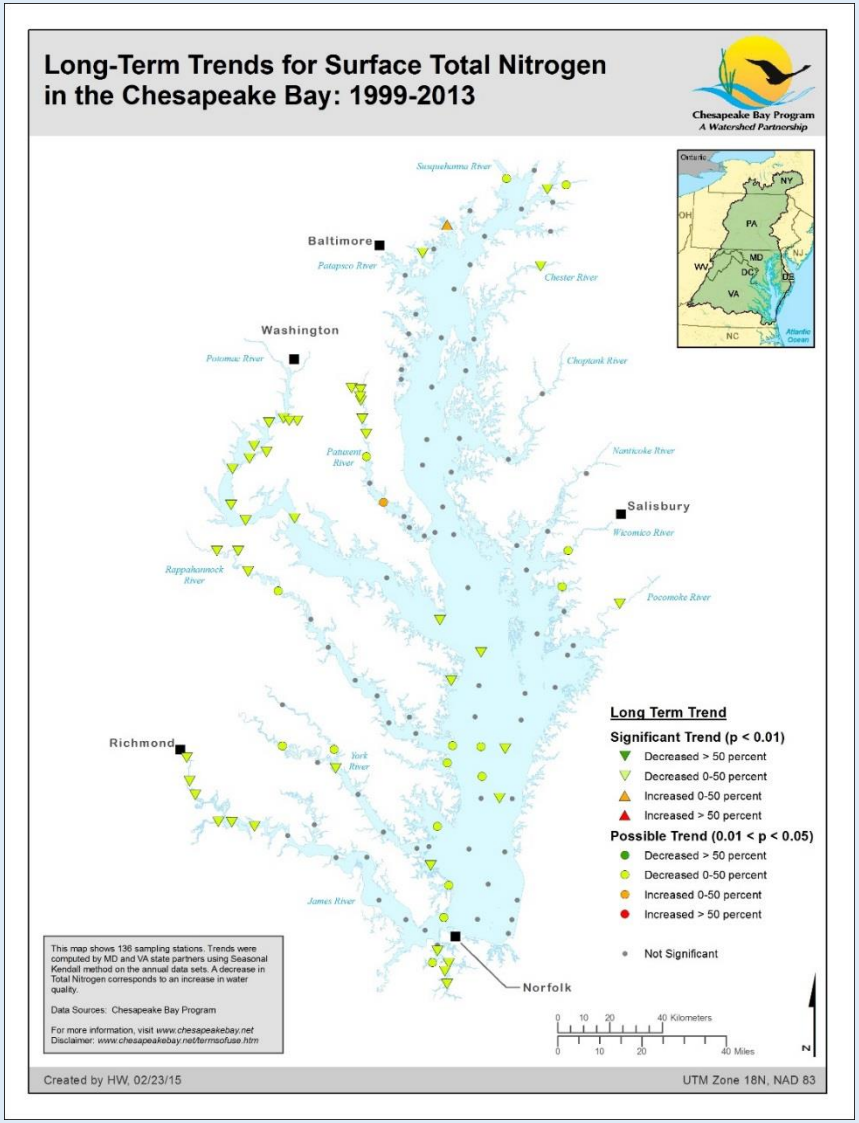
1. Measure progress
2. Explain water-quality changes
3. Enhance CBP models
4. Inform management strategies

Tidal Water Quality: Current Approach

- Seasonal Kendall used by CBP, MDDNR and VADEQ since 1990s for tidal water quality trend analysis

- Beneficial features:
  - Allows for identification of monotonic trends
  - Good for outliers
  - Does not require a distributional assumption

Seasonal Kendall-based trend maps (Presented to WQGIT March 2015)

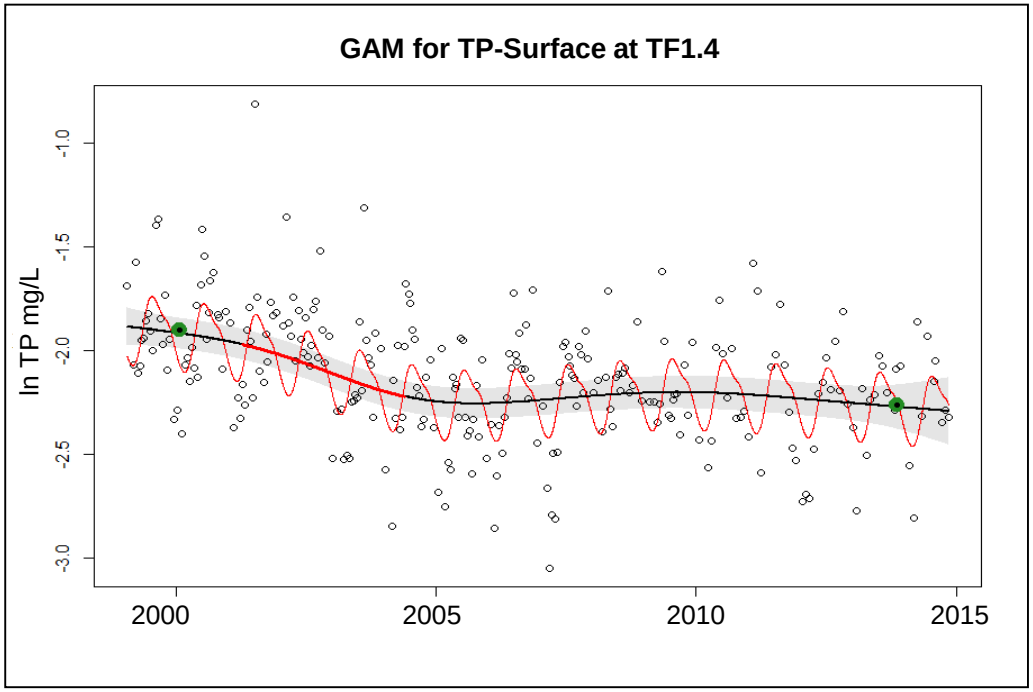


http://www.chesapeakebay.net/maps

Why a method change?

Based on lessons learned from current approach, looking for a method that:

- Is flexible enough to represent many possible patterns, *including trends that have changed direction over time*
- Is able to model non-linear relationships
- Generates a statistical confidence measure
- Can be used to test "factors affecting trends"



GAMs: Steps Towards Implementation to Tidal Chesapeake Bay

2013

- Evaluations of trend method options at CBP and select GAMs as a viable option

2014

- March: STAC workshop on Explaining Trends
- All year: Meetings with state partners who do current trend analysis and USGS-WRTDS team
- All year: Test GAM capabilities
- October: Introduce GAMs at WQGIT meeting

2015

- All year: Continue to test GAMs and meet with state partners
- Spring: Mainstem pilot application and compare to SK
- Summer: Tributary pilot application and refining uncertainty output
- September: Present Version 1 method to WQGIT
- Fall: STAC review
- December: Version 1 available in R tool

2016

- Version 2 and 1985-2015 application
- Begin R&D applications to explaining trends project

Version 1: Approach

With a GAM, a response variable is modeled as the sum of multiple nonlinear (or linear) functions of explanatory variables

GAM 1: Linear trend with seasonality

```
y = linear(date) + s(doy)
```

GAM 2: Smoothed trend with seasonality

```
y = linear(date) + s(date) + s(doy)
```

GAM 3: Seasonally-varying smooth trends

```
y = linear(date) + s(date) + s(doy)
    + Interaction(date, doy)
```

s = spline smooth functions
doy = day of year

Version 1: Approach

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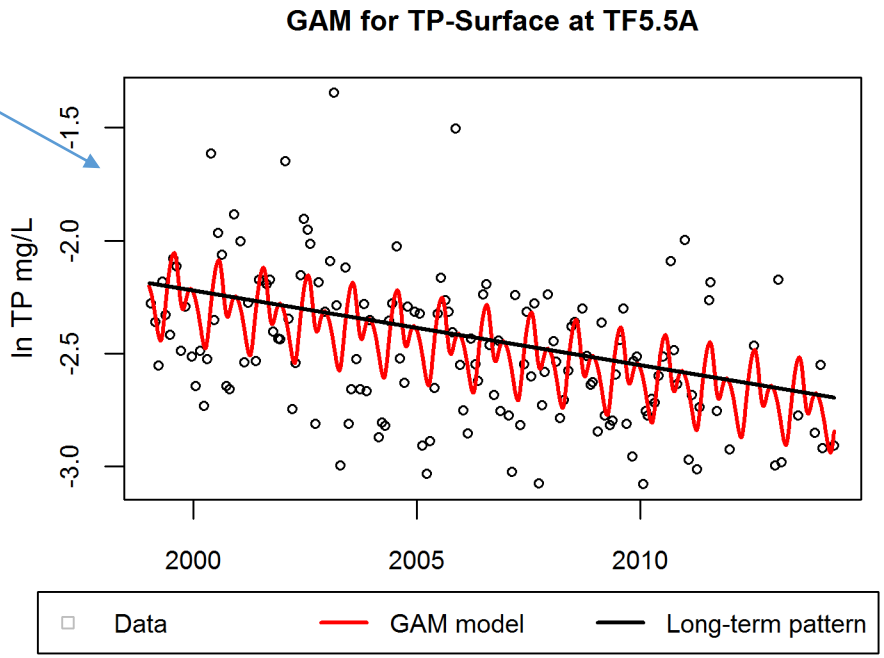

GAM1 is a good fit because there is a smooth seasonal cycle, but the overall trend is a linear decrease.

Version 1: Approach

GAM 1: Linear trend with seasonality

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GAM 2: Smoothed trend with seasonality

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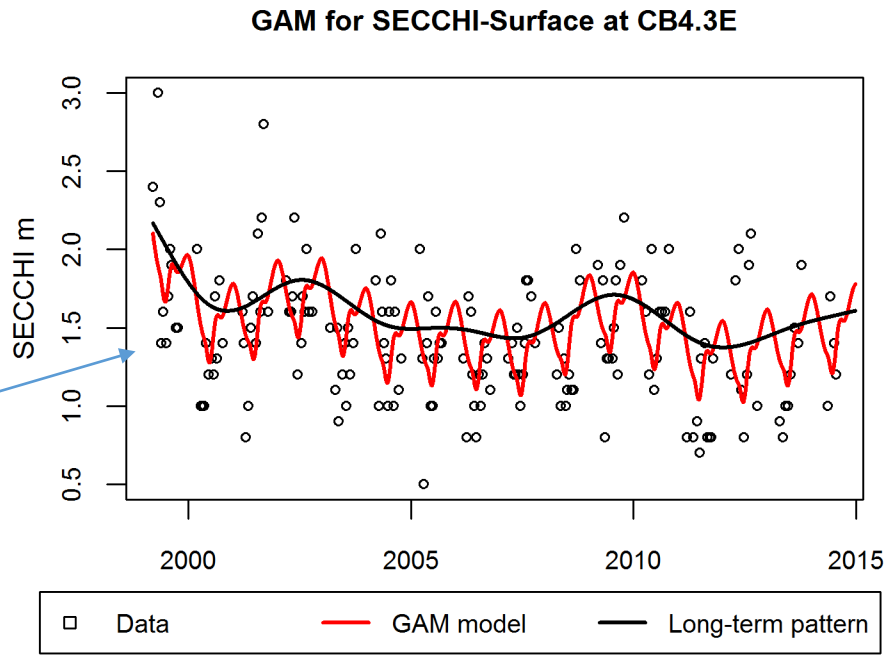

GAM2 is a useful because there is a significant, smoothly-varying pattern over time.

s = spline smooth functions
doy = day of year

Version 1: Approach

GAM 1: Linear trend with seasonality

```
y = linear(date) + s(doy)
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GAM 2: Smoothed trend with seasonality

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GAM 3: Seasonally-varying smooth trends

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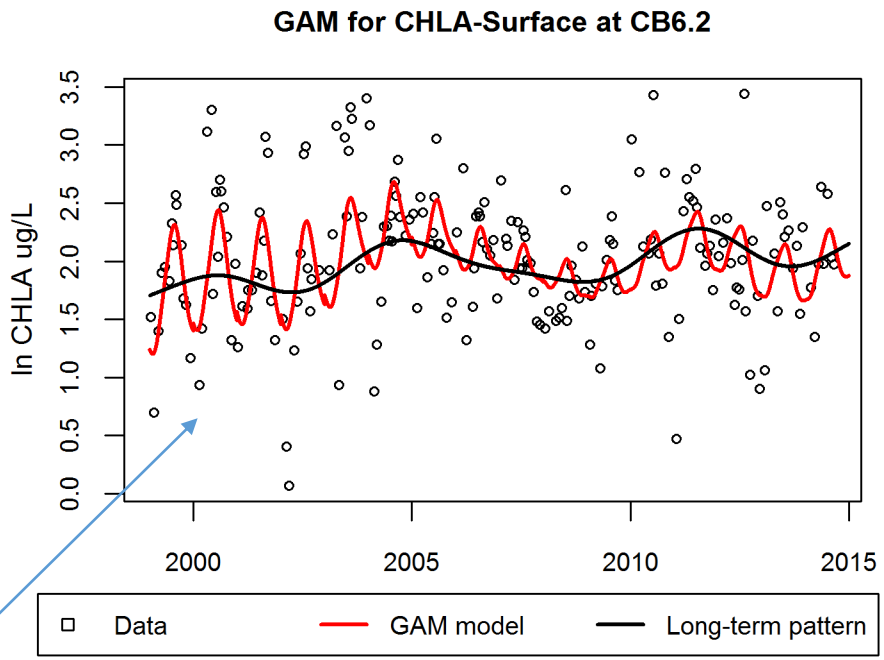


GAM3 is a good choice because the shape of the seasonal cycle is changing over time.

s = spline smooth functions
doy = day of year

Version 1: Full Tidal Application

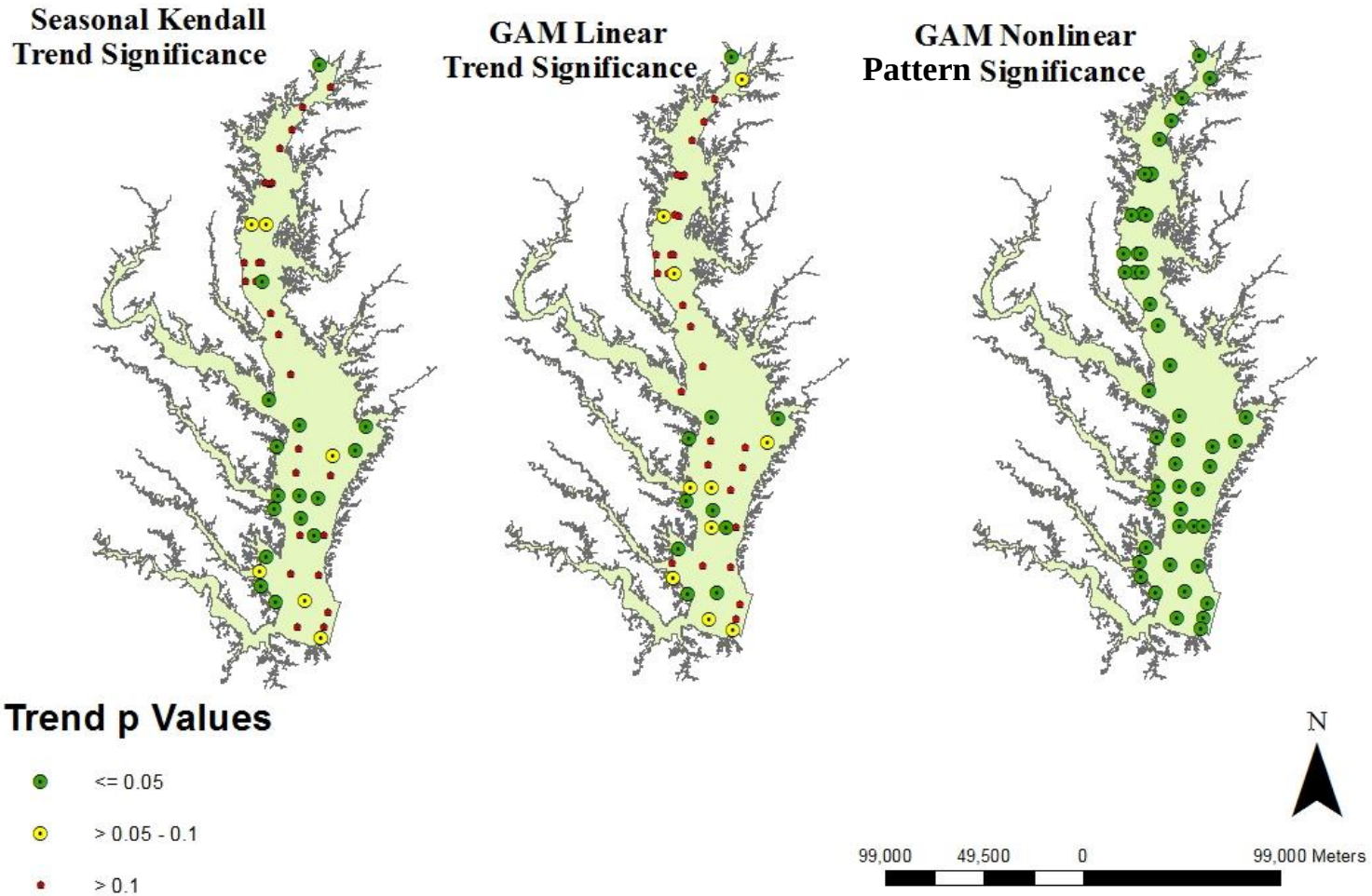
- Fit the GAMs to all mainstem and tributary stations using data from 1999-2014
  - Secchi disk depth; Surface and Bottom TN, TP, DO, and chlorophyll-a
  - Can compare the 3 models using model-fit statistics

- Conducted GAM/Seasonal Kendall comparison for mainstem to answer: "Are the overall trend results going to change with GAMs?"
  - Answer: No, because the linear components of the methods perform similarly
  - Any systematic differences appear to be when the data pattern is non-linear

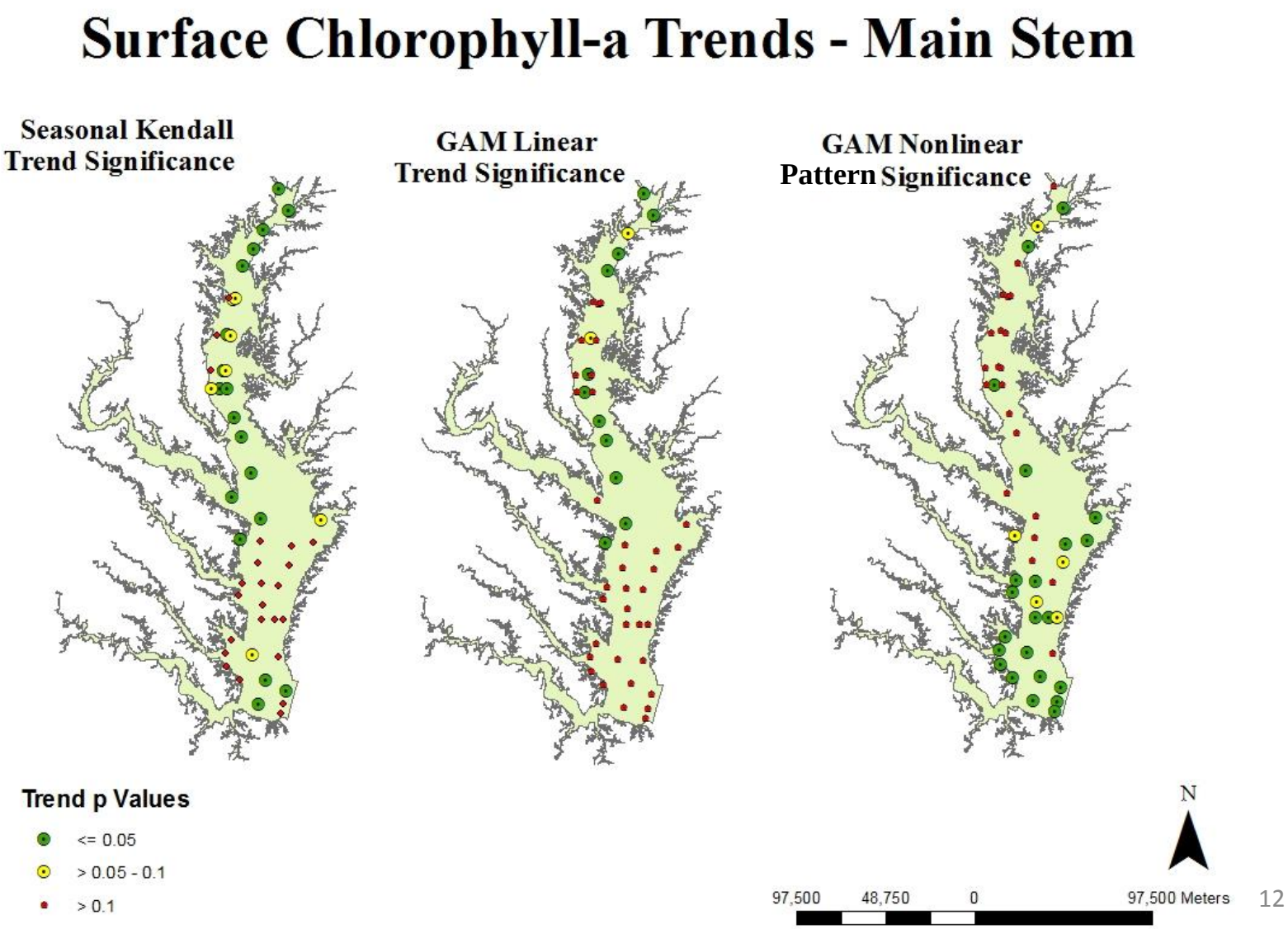
- Developing ways to present and evaluate full set of GAM output

Seasonal Kendall/GAM Comparison

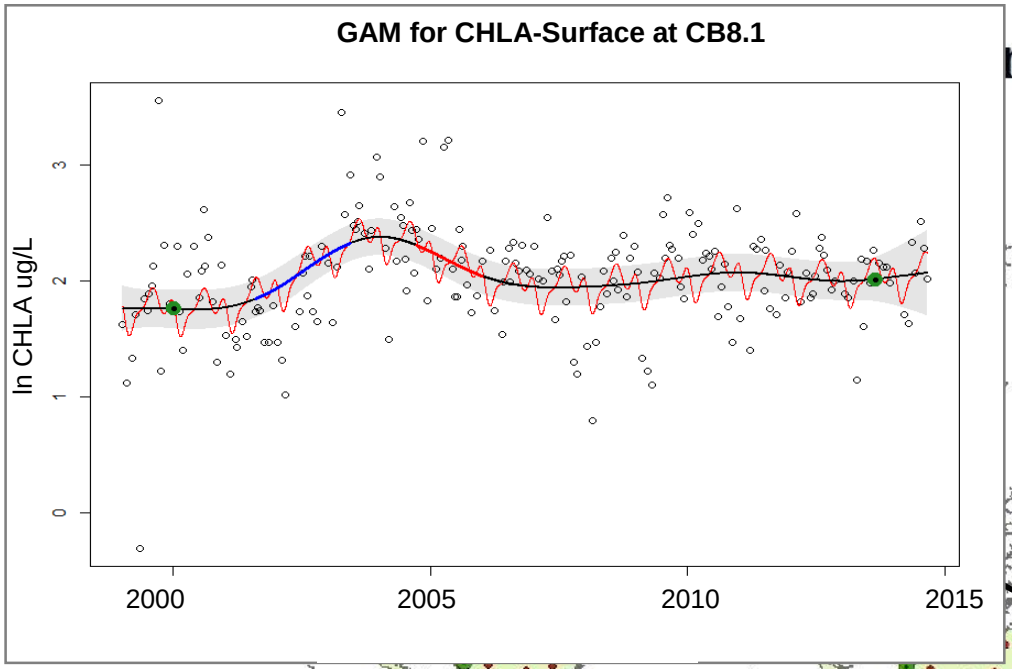
Surface Total Nitrogen Trends – Main Stem



Seasonal Kendall/GAM Comparison



Seasonal Kendall/GAM Comparison



rends - Main Stem

GAM Nonlinear
Pattern Significance

Trend p Values
<= 0.05
> 0.05 - 0.1
> 0.1

N

97,500 48,750 0 97,500 Meters

Seasonal Kendall and GAM features/applications side-by-side	SK	GAM V1	Future GAM versions
Temporal trend identification			
Identification and significance of long-term trends	x	x	x
Slope and direction of a trend	x[a]	x	x
Pattern and confidence bounds on long-term temporal pattern		x	x
Significance of explanatory variables (e.g., date, season)		x	x
Incremental periods with significant trends		x	x
Accounting for residual temporal autocorrelation			x
Application			
Trends in mainstem and tributary 1999-2014 water quality data	x	x	x
Account for step changes and varied detection limits (i.e., use all data 1985-present)	x[b]		x
Flow as an explanatory variable (optional)		x[c]	x
Include other explanatory variables for hypothesis testing			x

[a] Sen slope test performs this for the SK approach
[b] SK is applied to pre-1999 using data censoring and block-approaches
[c] An approach is implemented, but some modifications are needed

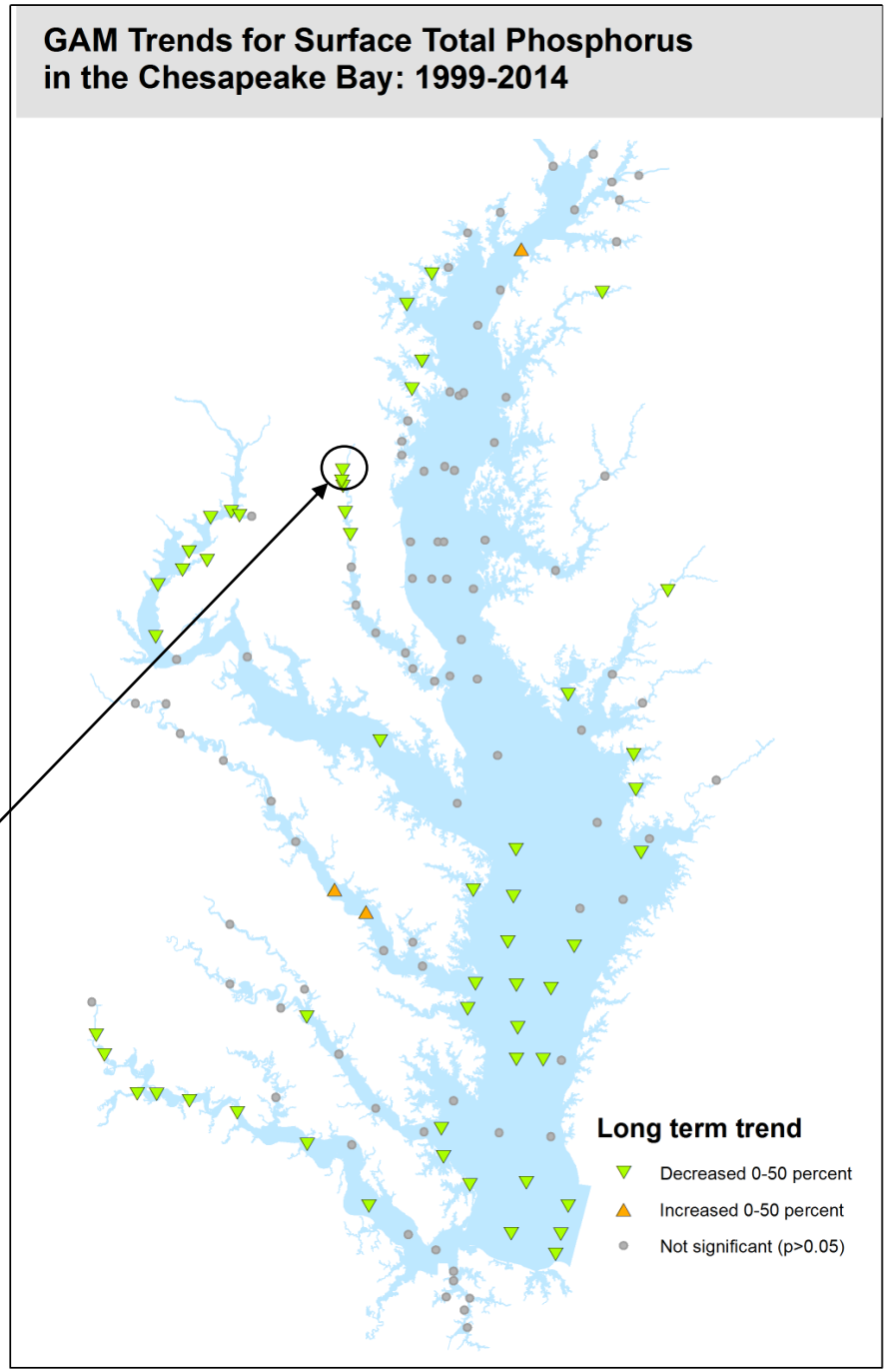
Version 1: Results

Layers of output:

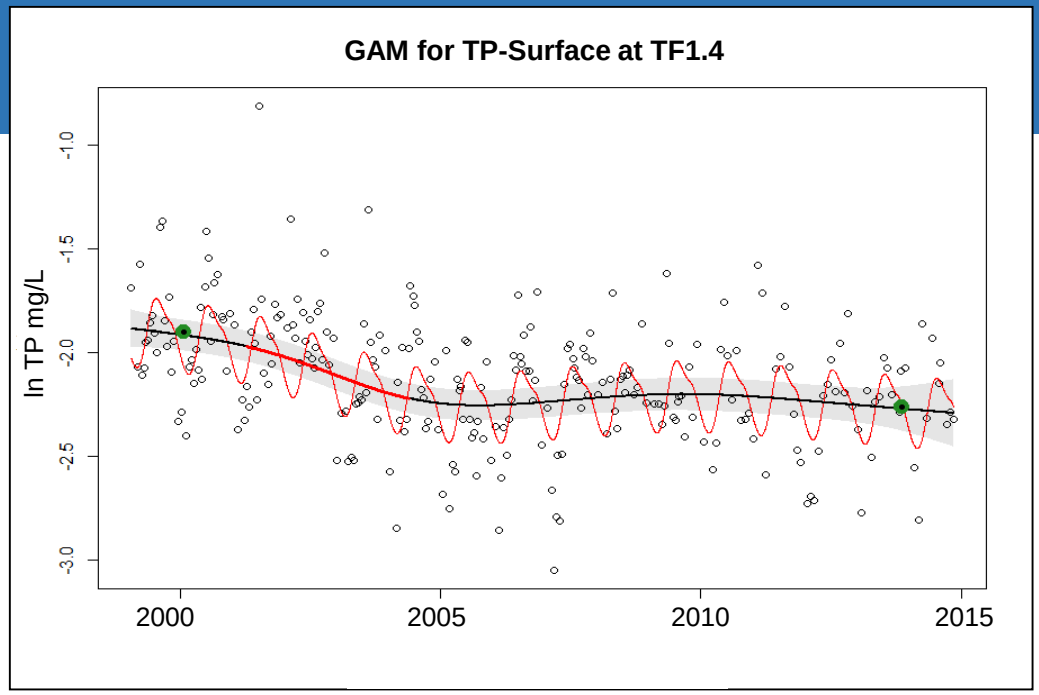
1. Is there a trend over a given time period?
   - Identification and significance of long-term trends
   - Slope and direction of a trend

Example: TF1.4 TP Surface 1999-2014

```
Baseline log mean = -1.90
Current  log mean = -2.26
Estimated log difference = -0.36
Std. Err. log difference = 0.060
Confidence interval for log difference =
(-0.48 , -0.25)
Difference p-value = <0.0001
Percent Change Estimate =  -30.6 %
```



Version 1: Results



Layers of output:

2. What does the trend look like?

- Pattern and confidence bounds on long-term temporal pattern
- Incremental periods with significant trends
- Significance of explanatory variables

Example: TF1.4 TP Surface 1999-2014

GAM output

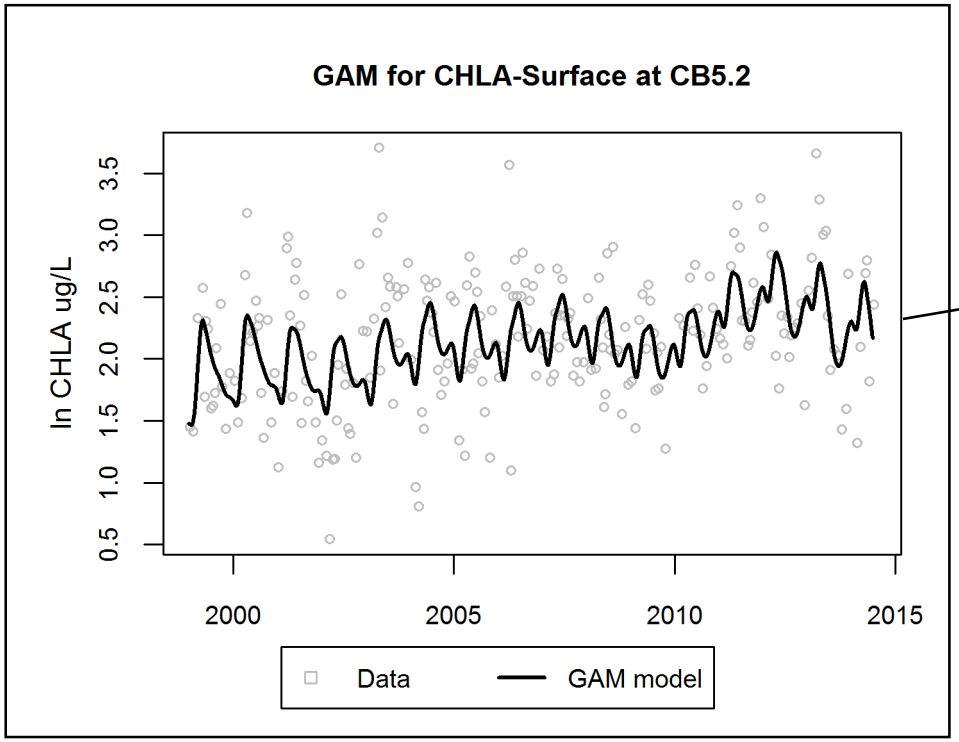
Source	edf	F-stat	p-value
linear(date)	1	0.69	0.40
s(date)	3.74	5.97	<0.0001
s(doy)	3.83	8.21	<0.0001

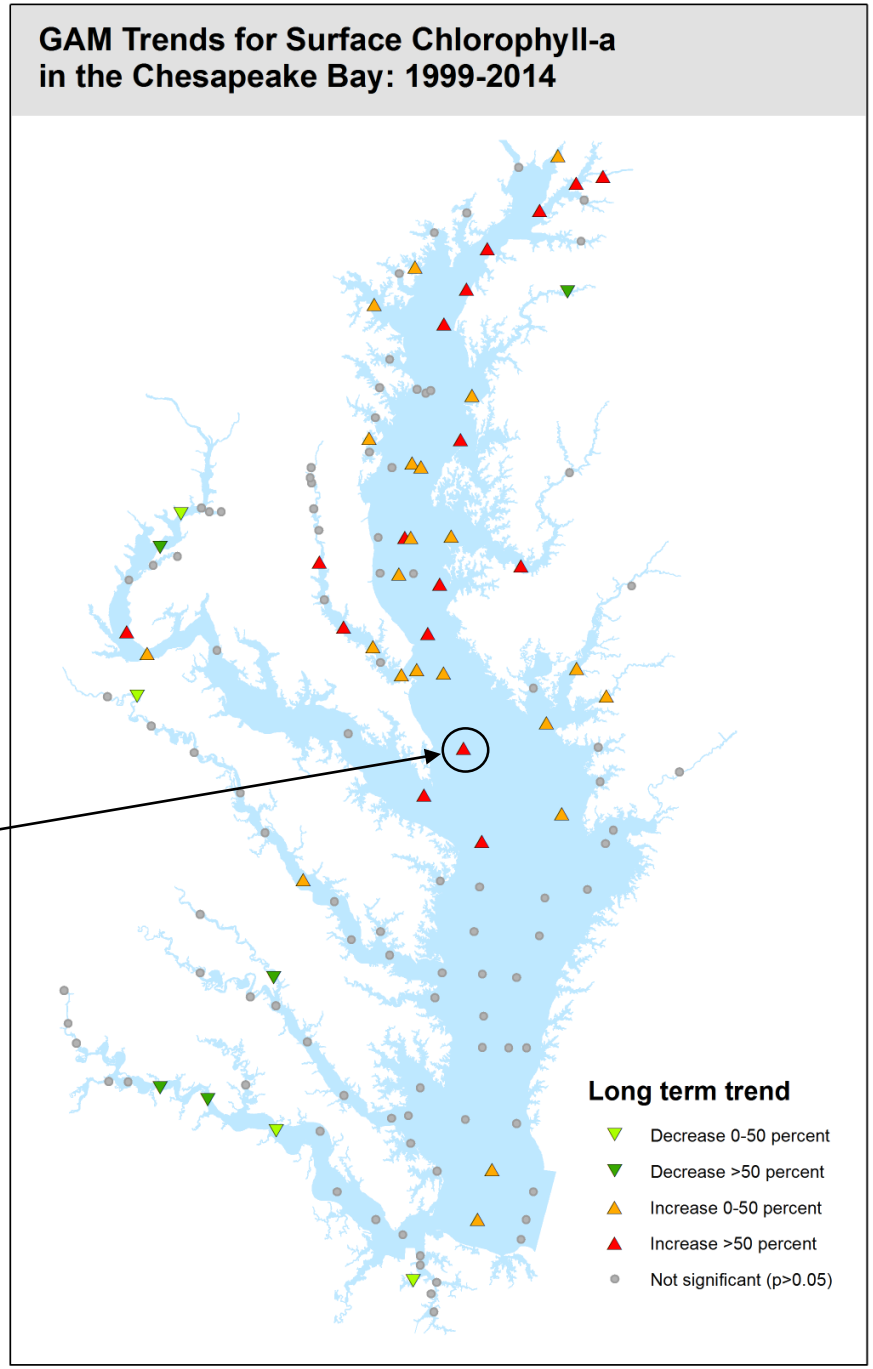
AIC 12.8
root mean-square error = 0.24
adjusted r-square = 0.36

Version 1: Results

Layers of output:

3. Is there a seasonal difference in the temporal trend?





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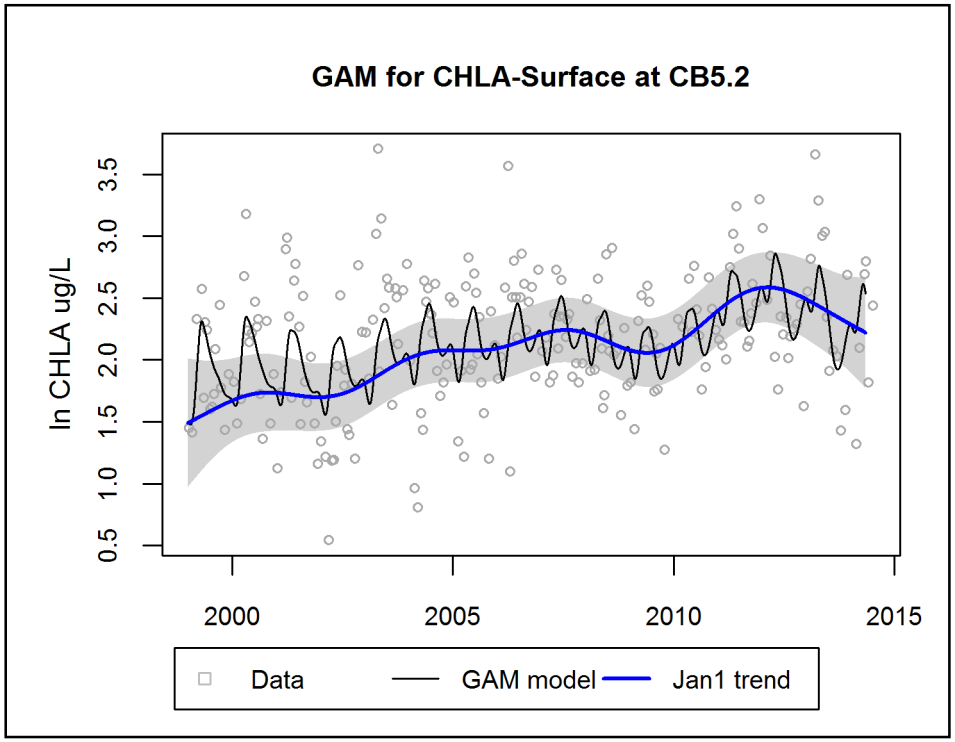

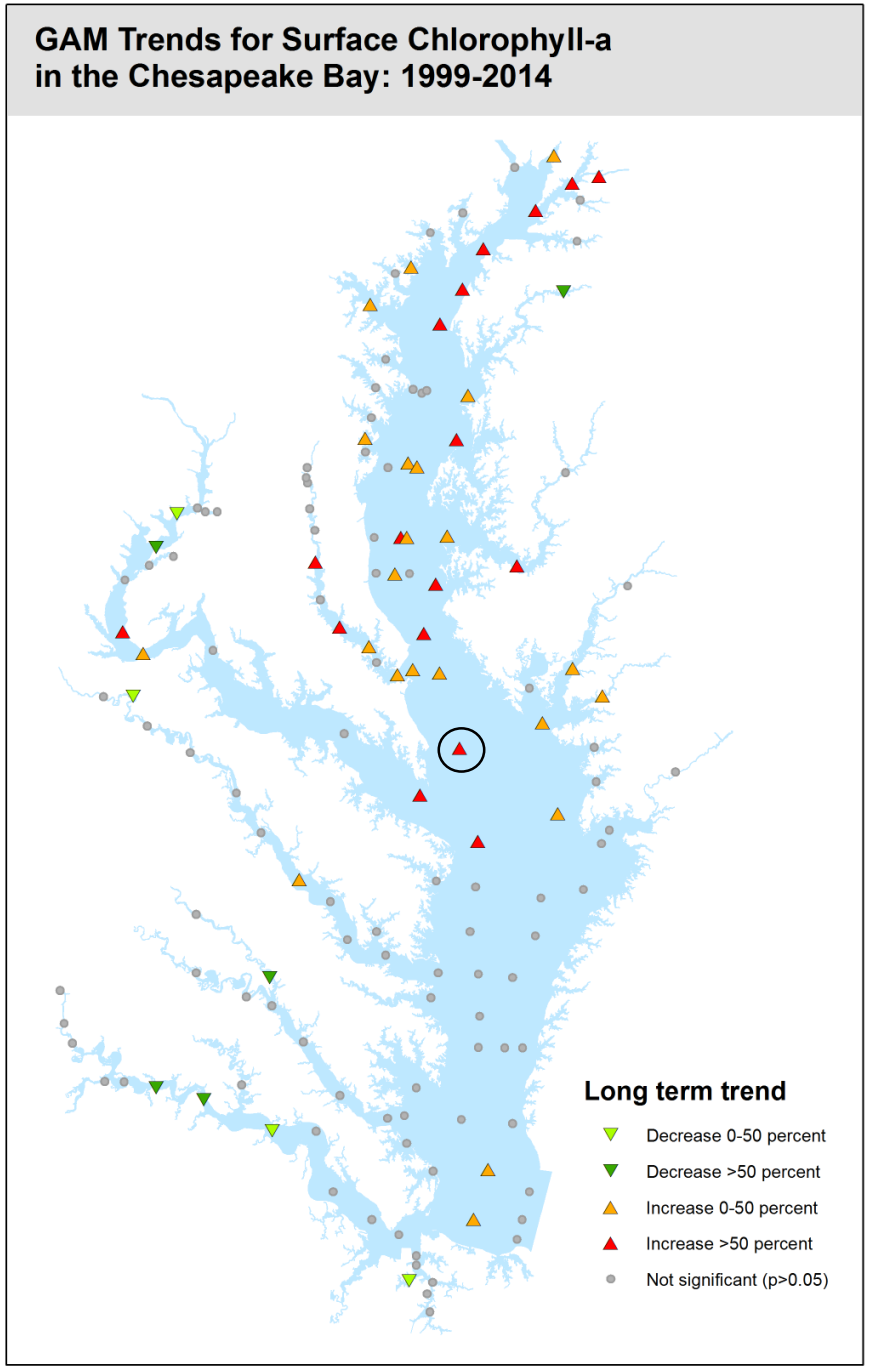

Version 1: Results

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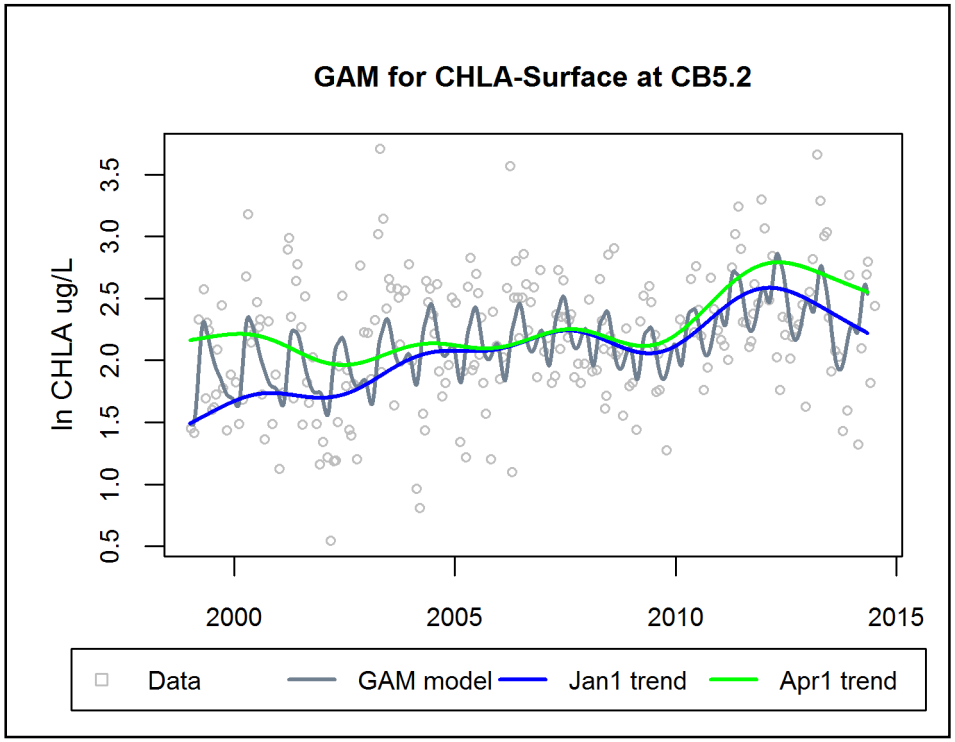

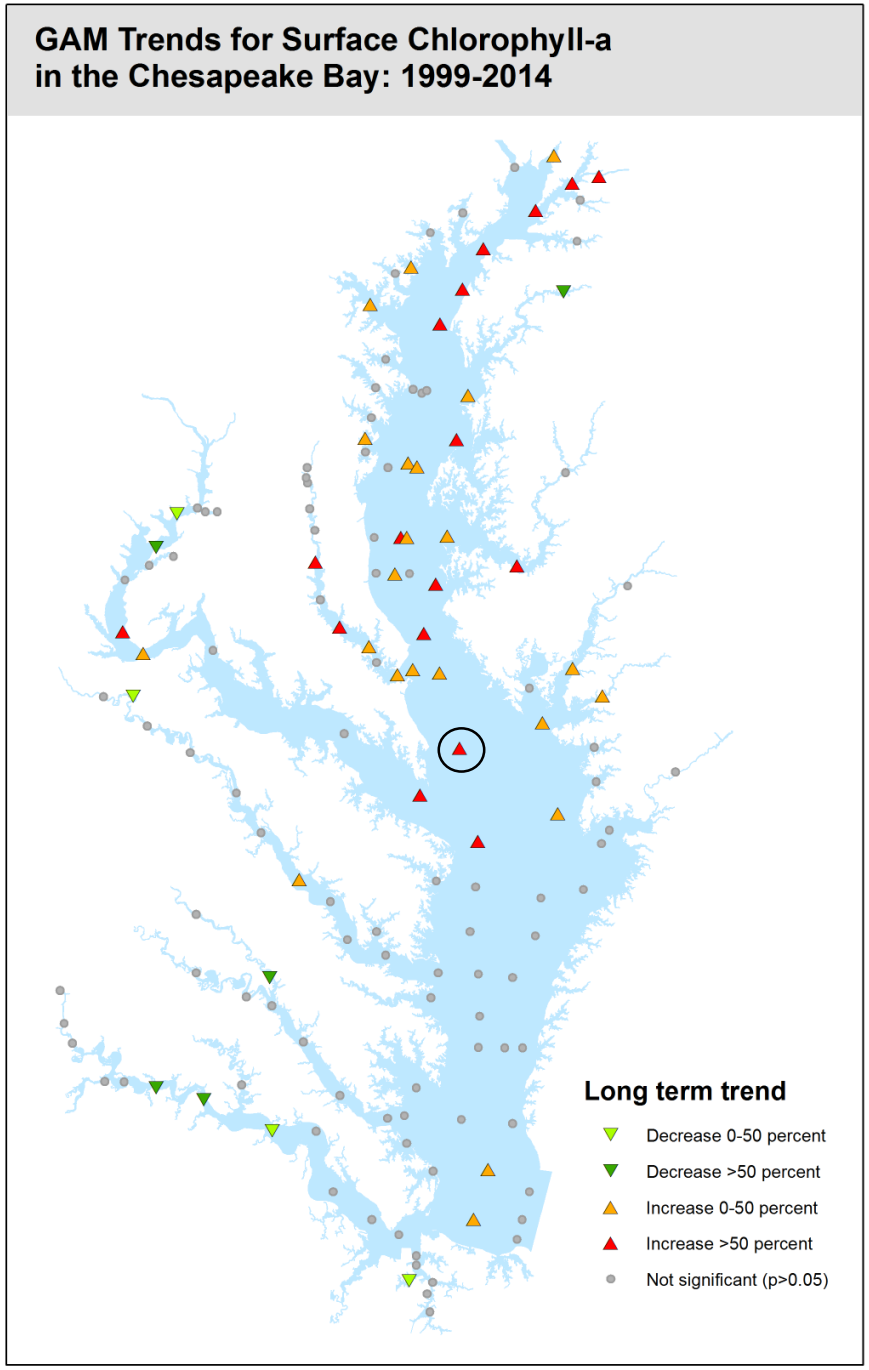

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Layers of output:

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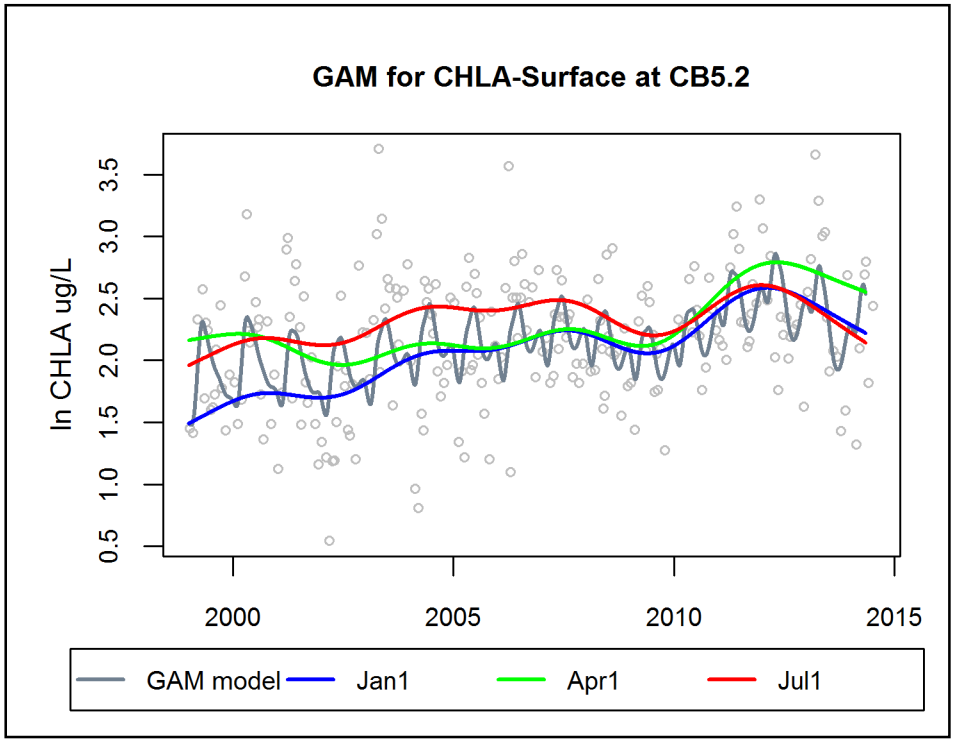

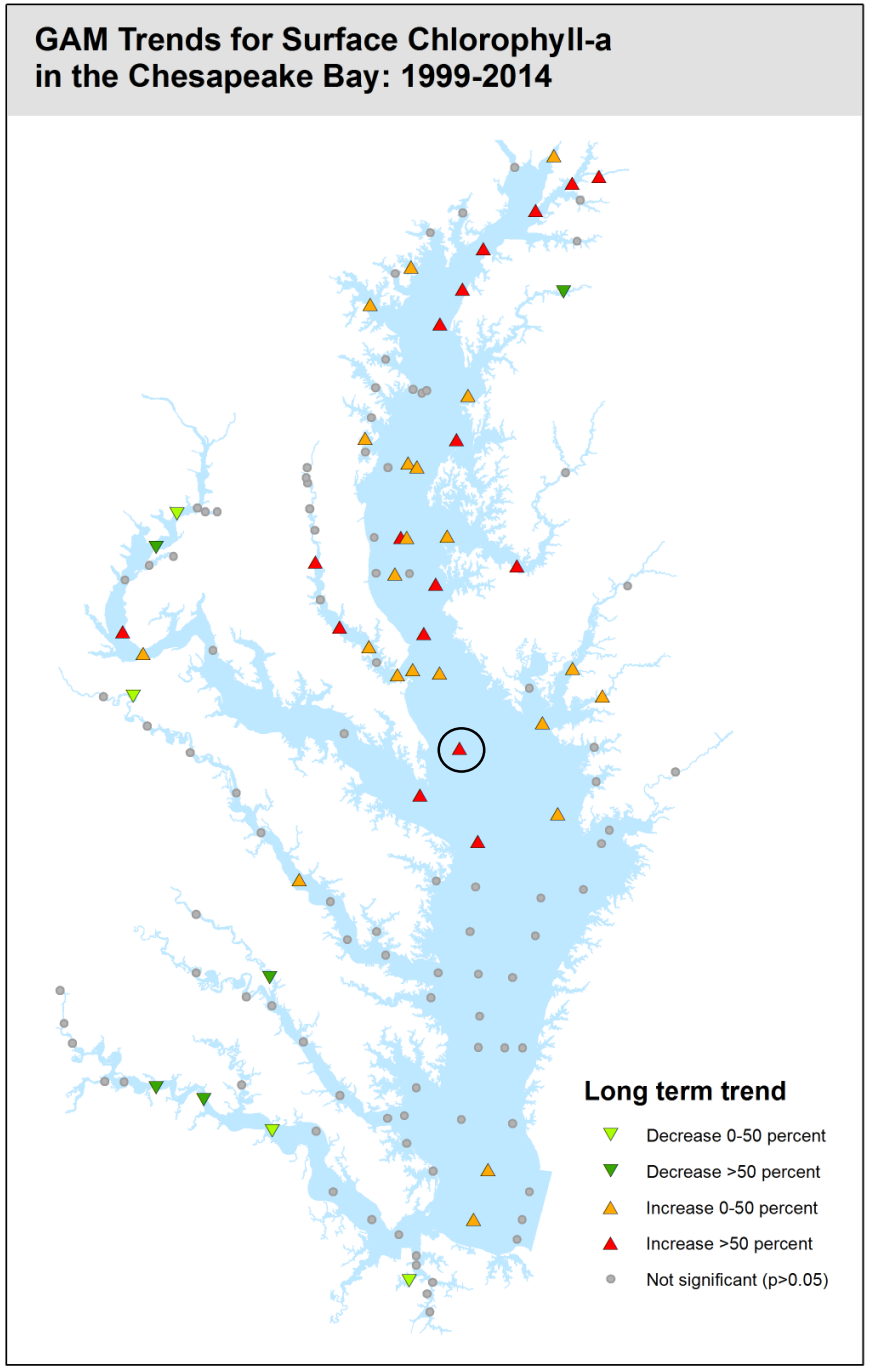

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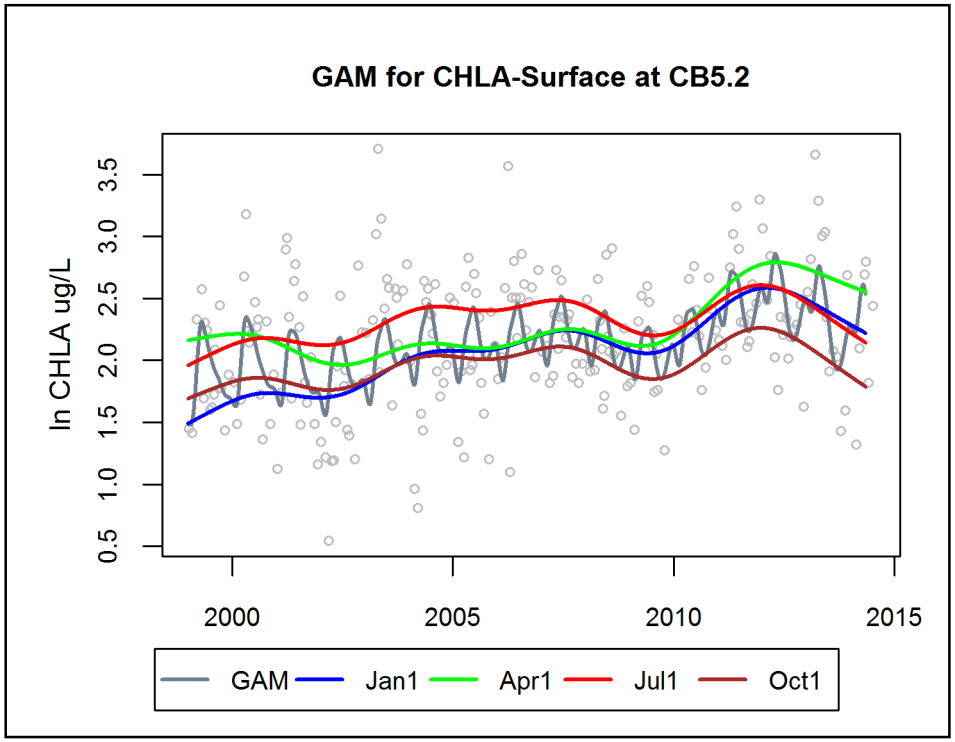

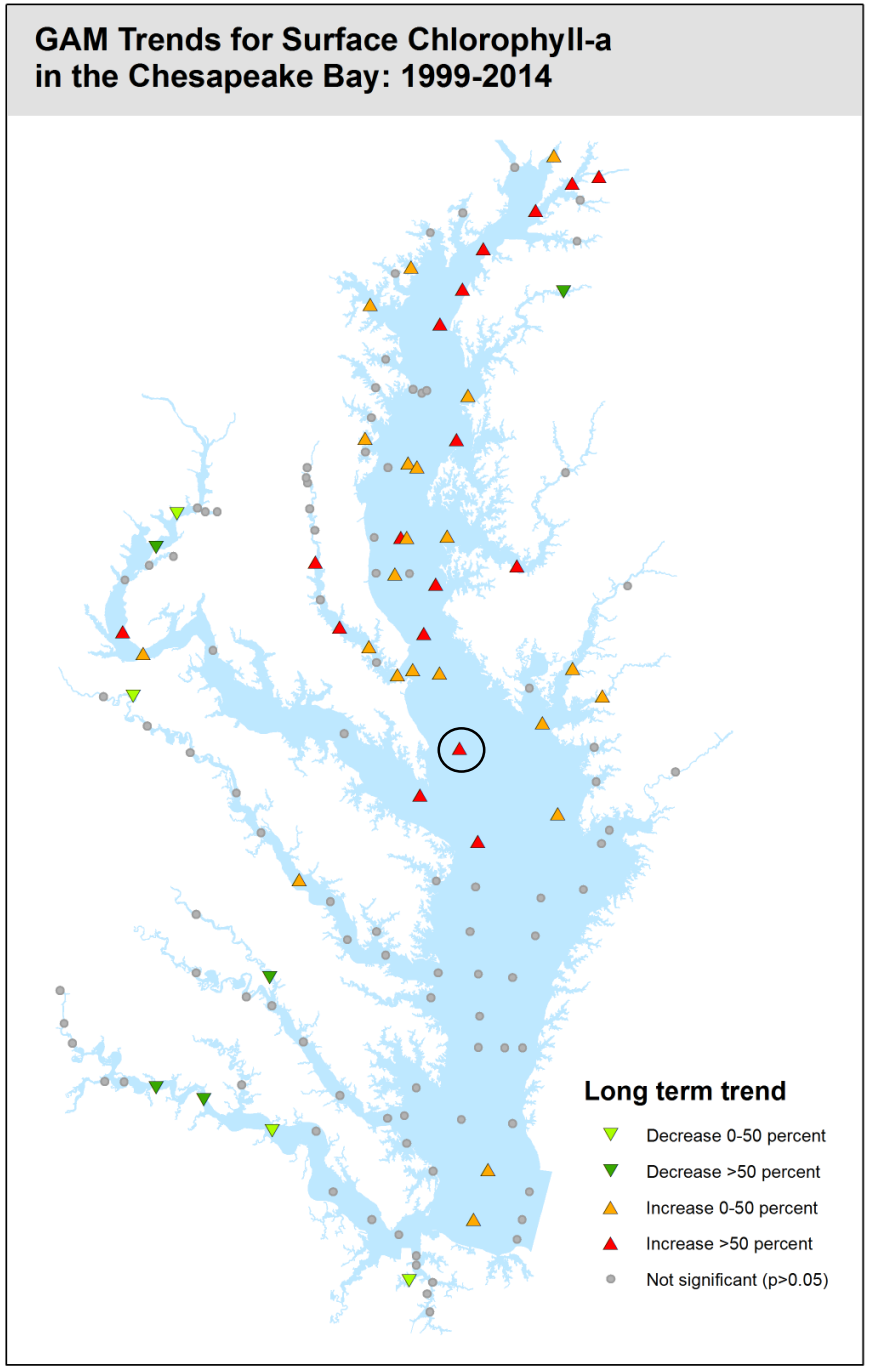

Version 1: Layers of Information

1. Is there a trend over a given time period?
2. What does that pattern look like over time?
3. Is there a seasonal difference in the temporal patterns?

Question: How can we most effectively share these layers of information without being overly complicated?

Next Steps

- GAM tool in R
  - First draft end of the week
  - Updated version end of November
- Version 2 GAM approach for tidal stations
  - Finalize flow as explanatory variable approach
  - Application to 1985-present
- Applications for factors explaining trends
  - Examining V1 results will help target further analyses
  - Work begun to use GAMs with nutrient inputs and climatic factors to explain trends
  - Doing this hand-in-hand with the research community (ITAT)