Statistical Analysis of BMP Effectiveness in the Cannonsville Watershed using SWAT as a Control Site

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Outline

• A water quality challenge
• Paired Analysis of R-Farm data
• Analysis of Cannonsville watershed using SWAT as a control site
• Conclusions
A Water Quality Challenge

• Problem: eutrophication of surface water in NYC drinking water reservoir

• Cause: phosphorus losses from agriculture

• Consequence: increased growth of algae and weeds resulting in poor drinking water quality
Two Primary Strategies

- **Watershed Management**
  - Land use change
  - Best management practices
    - Buffer strips
    - Precision feeding
    - Fencing
    - Critical source area management

- **Water Treatment**
  - Construct filtration plant in NYC to treat water
  - Cost estimated to be between $5-10 billion
BMP Implementation

- In Cannonsville basin, widespread BMP implementation began in mid 1990s
- Majority of farmers in the basin are now implementing BMPs
- Financial assistance for farmers provided by government agencies
Are BMPs working?

Statistical analysis of BMP effects

1. R-Farm: a small land unit
2. Cannonsvilles watershed: large area
R-Farm Analysis – What we did

- Automated data collection installed 1993
- BMPs installed 6/95-10/96
- Statistical analysis of BMP effectiveness

Bishop et al. 2005. *Journal of Environmental Quality*
Variability in Event Flows

Bishop et al. 2005. *Journal of Environmental Quality*
Variability in P Loads
R-Farm Analyses

- Univariate Matched Load Model
- Bivariate Matched Load Model
- Multivariate Matched Load Model
Univariate Matched Load Model (EPA, 97)

\[
\ln(P_{ti}) = a + b \ln(P_{ci}) + fk_i + \epsilon_i
\]

\(P_{ti} & P_{ci} = \text{phosphorus loads for farm & control}\)
\(a, b, f \text{ constants; } k_i = 0 \text{ or } 1; \epsilon_i = \text{error}\)

- Match phosphorus loads in test watershed with loads in control watershed
- Fit model to entire data set
- Include indicator variable \(k_i\) for BMPs
- Applied model to seasonal + full year data sets
Bivariate Matched Load Model

\[ \ln(P_{ti}) = a + b \ln(P_{ci}) + c \ln\left(\frac{Q_{ti}}{Q_{ci}}\right) + f k_i + \varepsilon_i \]

- \(Q_{ti}/Q_{ci}\) accounts for influence of differences in flows between the two sites: a forest does not always act like a farm site.
- Same interpretation of results
  - %Reduction = 100 [ 1-exp(f) ]

Bishop et al. 2005. *Journal of Environmental Quality*
Model Performance for PP

Bishop et al. 2005. *Journal of Environmental Quality*
Bishop et al. 2005. *Journal of Environmental Quality*
Bivariate Matched Load Model

- Significant improvement in model performance over univariate model
- Detectable BMP effects for all cases except
  - Fall TDP
  - Spring, Fall PP

Bishop et al. 2005. *Journal of Environmental Quality*
Multivariate Matched Load

\[
\ln(P_{ti}) = a + b \ln(P_{ci}) + c \ln\left(\frac{Q_{ti}}{Q_{ci}}\right) + \\
\quad d \ln(\text{peak } Q_{ti}) + e \ln(Q_{Rti}) + f k_i + \\
\quad g k_i \left[ \ln(P_{ci}) - m \right] + \varepsilon_i
\]

- Include multiple covariates to control for imbalances in event flow, peak and average flow rates, and changes in regression slope for pre/post BMP periods

Bishop et al. 2005. *Journal of Environmental Quality*
Model Performance for TDP

Adjusted $R^2$

- Winter
- Spring
- Summer
- Fall
- Full Year

Bishop et al. 2005. *Journal of Environmental Quality*
Results with Three Models

- Bivariate model better than univariate matched-load (paired) model.

- Multivariate model fit better than bivariate matched-load (paired) model, though sometimes only slightly.

- Detectable BMP effects for all cases except
  - Fall TDP
  - Spring, Fall PP

Bishop et al. 2005. *Journal of Environmental Quality*
Conclusions from R-Farm Analysis

- In general, seasonal multivariate model best approach, though sometimes only slightly better than matched bivariate or single watershed models; $R^2$ values of 80-90%
- Univariate matched load model performed poorly
- Inclusion of flow term significantly improved matched load models
- Overall reduction in nutrient losses:
  - 43% TDP
  - 29% PP
Statistical Analysis of Cannonsville Watershed Data using SWAT as a control site
Analysis of Cannonsville Data

- Paired Watershed Analysis
  - Previous studies have used smaller catchments ranging in size from 2 to 1,000 ha
  - Where do you find a control site for the 120,000 ha Cannonsville basin?
  - A paired analysis with two 120,000 ha watersheds would cover an area equal in size to Rhode Island
Environmental Data

- Flow data collected at USGS gage at Walton
  - Daily averages derived from measurements taken every 15 minutes

- TDP concentrations measured at NY DEC gage at Beerston
  - Sampling frequency varies with stage at USGS gage at Walton
  - Loads computed as product of flow and concentration
Discharges, Time Periods

- WWTP loads provided by NY DEC
  - Seven consecutive daily samples from each month used to construct monthly averages

- All data converted first to daily time series

- Daily data then converted to biweekly averages to define events for statistical analysis

Note carefully

- Considered only dissolved Phosphorus: TDP
- Biweekly averages: 26 per year.
SWAT 2000 for Cannonsville

- SWAT is a widely used watershed simulation model designed for application in agricultural watersheds
- Used Tolson/Shoemaker SWAT2000 model of Cannonsville for this study

SWAT includes:
- Waste Water Treatment Plant discharges
- Herd Size (reduction)
- Rainfall-Runoff model
- Agricultural practices
SWAT as a Control Site

- Tolson and Shoemaker (2004)
  - SWAT model of Cannonsville initialized and calibrated for flow, sediment, and phosphorus
  - Validation period: 1991-1993

- BMP implementation in Cannonsville
  - Define pre BMP as 1991-1994
  - Define post BMP as 2000-2004
SWAT Results Biweekly TDP

Biweekly Average TDP Loads

- Pre-BMP
- BMP Implementation
- Post-BMP
- Measured Data
SWAT– Prediction Error

Biweekly Average TDP Prediction Error

Error (Predicted - Observed) (kg)

Pre-BMP  BMP Implementation  Post-BMP

Time

Paired Analysis Using SWAT

Dillon Cowan M.S. thesis: August 2008

• SWAT calibrated: 1994-2000
• Pre-BMP period: Oct 1991-Dec ‘94 (k=0)
• Post-BMP period: Jan 2000-Sept ‘04 (k=1)

For this analysis SWAT did not have agricultural BMPs. We are looking to see their effect show up in the data.
Dillon Cowan M.S. thesis

- Match SWAT loads (w/o BMP) with observed loads to see if BMPs show up.

- Perform statistical analyses
  - Univariate Matched Load Model
  - Bivariate Matched Load Model
  - Multivariate Matched Load Model
Different flows pre- & post-BMP

Flow rate (cms)
Different TDP loads, but why?
TDP and Flow: a change

TDP and Flow: a change
TDP load and Flows time series

Event Flow Volume (MCM) vs. TDP Load (kg/day) for Event Number (pre bmp 1-84, post bmp 85-207)
TDP loads and WWTP Loads
Log-Linear Model Results

\[
\ln \left( P_i^m \right) = a + b \ln \left( P_i^s \right) + c \ln \left( Q_i^{m-\text{peak}} \right) + f k_i + g k_i \left[ \ln \left( P_i^s \right) - p \right] + \epsilon_i
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>a</th>
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<th>c</th>
<th>f</th>
<th>g</th>
<th>Adj. $R^2$</th>
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<tbody>
<tr>
<td>LLP</td>
<td>1.12</td>
<td>0.59</td>
<td>-</td>
<td>0.07 (ns)</td>
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<td>0.69</td>
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Log-Linear Model Results

- Residuals were graphically tested for heteroscedasticity and autocorrelation
- No significant heteroscedasticity detected
- Residuals were significantly correlated
- Addressed correlation using FGLS for AR(1) residuals

[Feasible Generalized Least Squares FGLS for AutoRegressive residuals with lag-1.]
Correlation of residual errors

$y = 0.5^*x - 0.0033$
Log-Linear Model Results

\[
ln(P_{i}^{m}) = a + b \ln(P_{i}^{s}) + c \ln(Q_{i}^{m,\text{peak}}) + f k_i + g k_i[\ln(P_{i}^{s}) - p] + \varepsilon_i
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Log-linear Phosphorus models LLP and LLP-I without Flow $Q_{i}^{m,\text{peak}}$ are poor. With LLP no significant BMP effect; With LLP-I including interaction, BMP effect positive!

LLP-F-I with interaction: g not significant
LLP-F is best model. But coefficient on SWAT- P Load only 0.09.
Log-Linear Model - Concerns

\[
\ln(P_i^{m}) = a + b \ln(P_i^{s}) + c \ln(Q_i^{\text{mpeak}}) + f k_i + g k_i [\ln(P_i^{s}) - p] + \epsilon_i
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LLP-F is best model. But coefficient on SWAT- P Load only 0.09.

All of the changes in Waste Water Treatment Plants wwtp and cattle population are in $P^s$; it received almost not weight. Reduction in P equal to $1-\exp[-0.66] = 55\%$ are too large.
Disaggregated model LP

\[ \ln(P_i^{m}) = \ln\left[a + b \left(\text{wwtp}_i\right) + \left(Q_{i}^{\text{mavg}}\right)^{c}\left(C_i^{g}\right)^{d}\exp\{h + f \ k_i\}\right] + \varepsilon_i \]

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<tr>
<td>LP</td>
<td>-1.87</td>
<td>0.35</td>
<td>1.02</td>
<td>0.13</td>
<td>-0.59</td>
<td>-</td>
<td>2.29</td>
<td>0.88</td>
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</tbody>
</table>

Model LP explicitly represents waste-water-treatment-plant (wwtp) loads
SWAT is used to estimate concentration of P net the wwtp loads
SWAT concentration is multiplied by measured average flow: Load = Q C

Thus SWAT used to explain likely variation in concentration.
Reasonable model structure. Fit well. Coefficients significant except interaction g
Residuals were correlated so used FGLS[AR(1)] for statistical analysis.

Reduction in P is about 1–\(\exp[-0.59]\) = 44%;
actually reduction 41.5% with 95% conf. interval [33.6%, 49.2%]
Single Watershed: no control

- Paired study not always feasible
- Single watershed models only use data from test site
- Simple

- Loss of paired covariate may not impact model performance, but can result in loss of important information
Single Watershed LS: results

\[ \ln(P^m_i) = \ln \left[ a + b \cdot \text{wwtp}_i + \left( Q^\text{mpeak}_i \right)^{c+g k_i} \cdot \exp\{d + f k_i\} \right] + \varepsilon_i \]

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<td>LS</td>
<td>-1.84</td>
<td>0.32</td>
<td>0.92</td>
<td>0.57</td>
<td>-0.70</td>
<td>-</td>
<td>0.89</td>
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<tr>
<td>LS-I</td>
<td>-2.42</td>
<td>0.38</td>
<td>1.03</td>
<td>0.18</td>
<td>-0.08</td>
<td>-0.17</td>
<td>0.90</td>
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Model LS/LS-I a little bit better than Model LP with R² of 88%

Model LS-I estimated load reduction of 56.5%, with 95% Conf. interval [32%, 73%]

But no adjustment is made for herd size. Thus the 41.5% reduction obtained with model LP that included SWAT concentration is more credible.
**Single Watershed Log-Linear**

\[ \ln(P^m_i) = a + c \ln(Q_{i}^{\text{peak}}) + f k_i + \varepsilon_i \]

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<tr>
<td>LLS</td>
<td>1.12</td>
<td>-</td>
<td>0.83</td>
<td>-</td>
<td>-0.93</td>
<td>-</td>
<td>0.86</td>
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<td>0.32</td>
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## Estimated reduction in TDP

<table>
<thead>
<tr>
<th>Model</th>
<th>Load Reduction (%)</th>
<th>CI [0.05]</th>
<th>Mean</th>
<th>CI [0.95]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>33.6</td>
<td>41.5</td>
<td>49.2</td>
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<tr>
<td>LS-I</td>
<td>31.9</td>
<td>56.5</td>
<td>73.4</td>
<td></td>
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<tr>
<td>LLS</td>
<td>51.3</td>
<td>60.5</td>
<td>68.2</td>
<td></td>
</tr>
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</table>

Model LP includes wwtp, $Q_i^{m-\text{avg}}$, and SWAT concentration. \( R^2 = 0.88 \)

Model LS-I has wwtp and $Q_i^{m-\text{peak}}$.

Model LLS is \( \ln[P_{im}] = a + b \ln(Q_{im-\text{peak}}) + f_{ki} + \varepsilon_{i} \). \( R^2 = 0.86 \)
Conclusions

- We can use a simulation model as a control site
- Multivariate models outperform univariate EPA models
- Modifications to structure of multivariate equations produce more physically meaningful model
- Simulated control loads provided important information about WWTPs and cows
- Use FLGS to correct for AR(1) residuals

[Feasible Generalized Least Squares FGLS for AutoRegressiveressive residuals with lag-1.]
Conclusions

- BMPs work!
- Documented a 41.5% reduction in TDP loads
- Proper representation of WWTP upgrades and dairy herd declines critical in obtaining proper estimate of BMP effectiveness
Acknowledgements

- NSF/IGERT
- USDA CEAP Project
- Dean Hively
- Bryan Tolson
- Pat Bishop and NYS DEC