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Drinking water treatment plant (DWTP) costs and source water quality: An updated case study

Matthew T. Heberling, Christopher T. Nietch, James I. Price,
Hale W. Thurston, Michael Elovitz

US Environmental Protection Agency, Office of Research and Development, Cincinnati, OH

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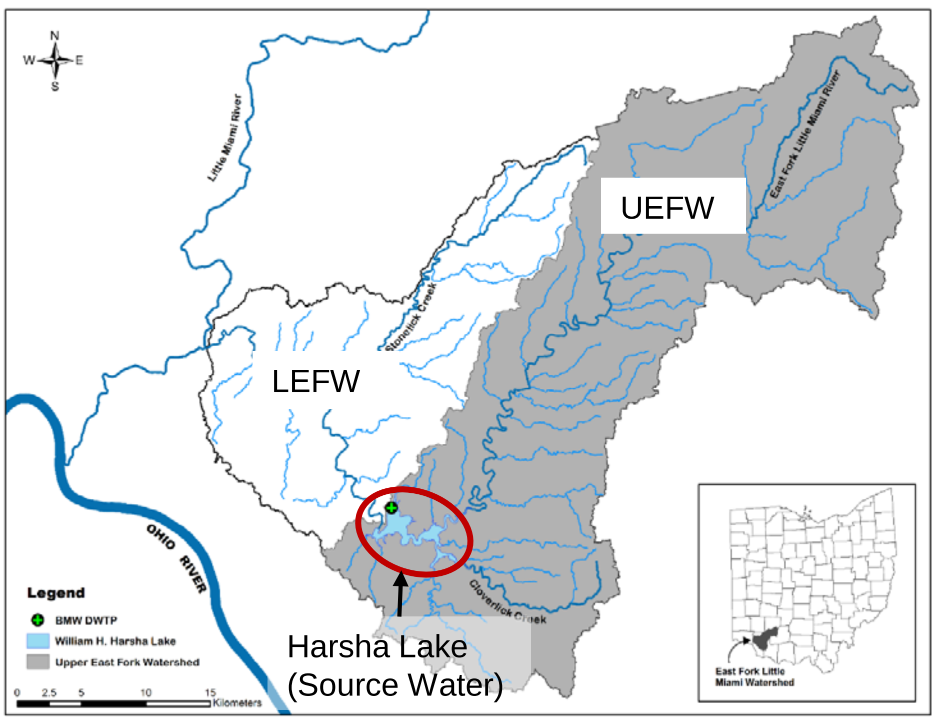
Background

- **Heberling et al. (2015)**
  - Developed a framework to compare costs:
    - **Drinking water treatment to source water protection**
  - Examine treatment costs with changes in source water quality, production, and seasonal variables
    - Five years daily data for one plant in southwest OH
  - Presents steps to estimate the incentives for source water protection vs. treatment on-site



General Steps for DWTPs

Step 1: Link changes in source water quality to changes in treatment costs

- Develop a cost function using data on raw water quality variables and treatment operations

Step 2: Link source water quality to watershed load reductions (through land use management)

- Connect watershed variables (e.g., phosphorus load) to source water quality variables governing treatment cost function (e.g., turbidity or total organic carbon [TOC])
- When treatment variables differ from watershed variables a "translation" is needed

Step 3: Estimate costs of the land use management (e.g., cover crops) that leads to watershed load reductions

Drinking Water Plant Intake Structure on Lake Harsha

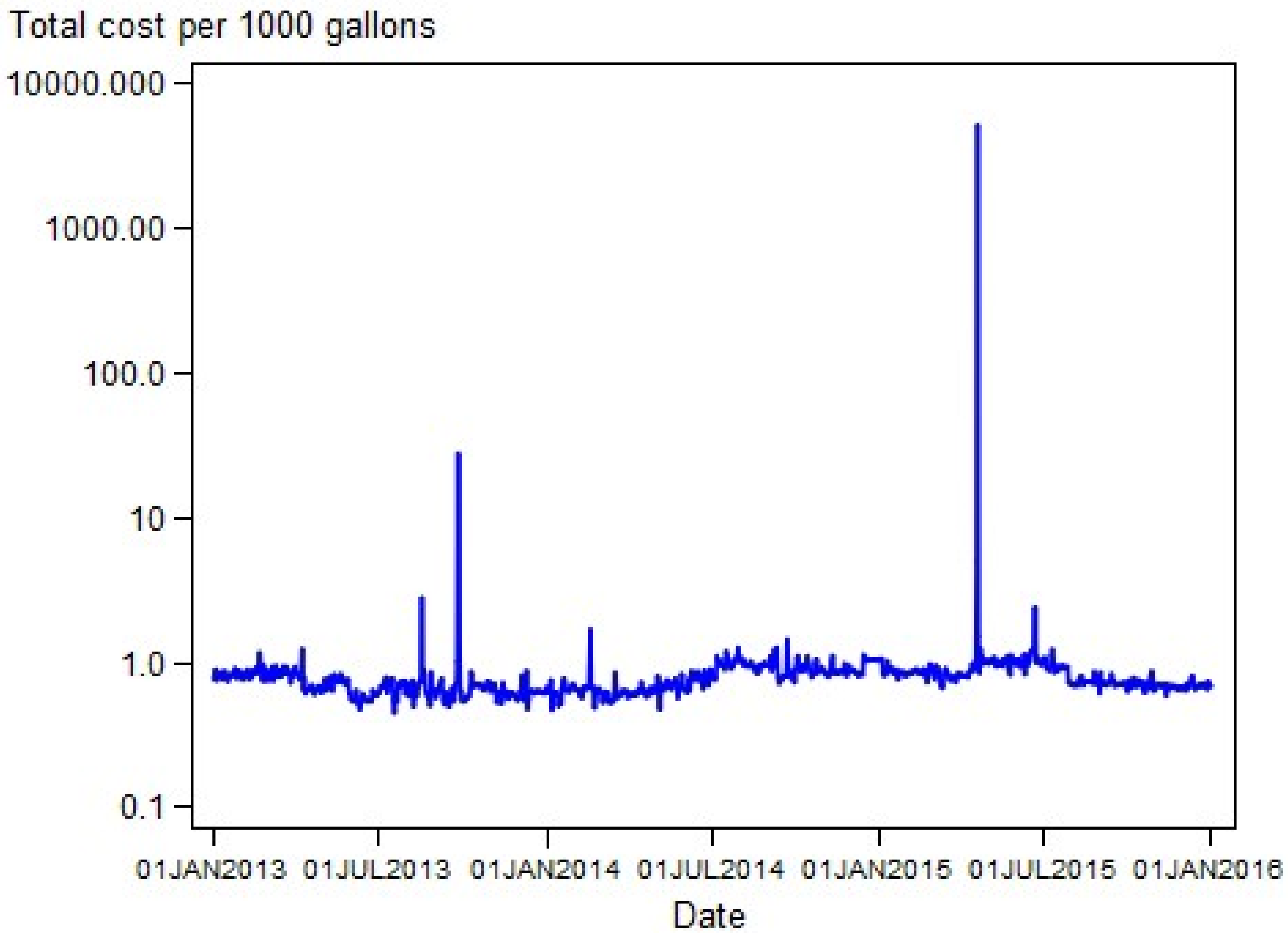
Case Study: Bob McEwen Water Treatment Plant (BMWTP)

- **Period 1 (Heberling et al. 2015)**
  - Before the period of significant source water quality degradation from Harmful Algal Blooms (HABs)
  - Clermont County Water Resources Dept. (operator logs, paper records, invoices)
  - US Army Corps. (reservoir characteristics)
  - Time series: 1826 daily observations, 2007-2011
- **Period 2 (Preliminary analysis)**
  - In 2012, BMWTP added a granular activated carbon (GAC) building, a significant investment
    - GAC used for addressing disinfection-by-products and algal toxins
    - Greater reliance on GAC filters might translate to increased costs creating need for source protection?
  - Same data sources as Period 1
  - Time series: 1095 daily observations, 2013-2015

Summary Statistics

Variable		Period 1 2007-2011 Mean	Period 2 2013-2015 Mean	Min	Max
FINAL	DW produced (MGD)	4.95	3.39	0.001	6.58
POOL	Pool elevation (ft)	731.73	731.90	728.90	752.67
GCPOOL	Pool minus guide curve	0.72	0.89	-1.85	23.67
pH		7.43	7.53	6.52	9.80
TURB	Turbidity (NTU)	11.42	6.72	0.07	73.00
RAWTOC	Raw water TOC (mg/L)	6.10	6.25	4.50	8.30
TOTALCOST/1000	Total costs per 1000 gal	0.55	5.51	0.45	5148.82
ChemCost/1000	Chem cost per 1000 gal	0.23	2.27	0.08	2272.19
PumpCost/1000	Pump cost per 1000 gal	0.23	0.79	0.07	636.65
GACCost/1000	GAC cost per 1000 gal	0.10	2.45	0.16	2239.97

Total Cost per 1000 Gallons of Final Flow (Dec 2016$)



Time Series Model

- Analyze daily costs using Error Correction Model (ECM)
  - Several commonly used time series models ignore the long-run equilibrium relationships predicted by economic theory
  - Tests for long-run and short-run effects
- Changes in one independent variable can have immediate effect on treatment costs, a long-run effect, or both
- Period 2 Model (2013-2015)

$$\frac{Cost}{1000\ gallons} = f\begin{pmatrix} FINAL, RAWTOC, TURB, pH, \\ GCPOOL, \\ ActualTOC, \\ SPR, CY13, CY14, two\ PROCESS \end{pmatrix}$$

ECM Results, Period 2

- **Preliminary results**
  - RAWTOC
    - 1% **decrease** in RAWTOC(≈ 0.06 mg/L) leads to an immediate 0.13% decrease in treatment cost
    - No change over future time
  - pH
    - 1% **decrease** in pH (≈ 0.08) leads to no immediate effect, but decreases treatment costs by 2.92% over future time
  - Spring months (April, May, June) associated with higher costs

Link Source Water to Watershed

- How does total phosphorus (TP) load effect source (raw) water?
  - Chose TP load because its linked to:
    1. Hillslope erosion (affinity for clay particles-> sediment load->turbidity)
    2. Algal blooms (increase TOC and pH)

- Time series analysis (polynomial distributed lag [PDL] model)

  - Period 2 Model (2009-2013)

$$RAWTOC = f\begin{pmatrix} TPLOAD, GCPOOL, SPR, SUM, \\ CY09, CY10, CY11, CY12 \end{pmatrix}$$

  - Need better translation among TP load, Algae, and Treatment Process

PDL Results, Period 2

- **Preliminary results (2009-2013)**
  - 1% reduction in TPLOAD (≈ 10.79 lbs/day) leads to 0.04% decrease in RAWTOC over the long-run (from weeks 2-9)
  - <u>$0.51</u> treatment cost savings from 1% annual TP load reduction
  - Cost to control 10.79 lbs/day for a year using cover crops = $11815--$106335 -> Price/lb = $3—$27 (i.e., 10.79*365*price)

View of 2012 HAB from DWTP intake

Conclusions

- Framework provides decision support for understanding cost drivers
  - **Period 1**: DWTP could reduce treatment costs in the short and long-run by reduction in source water <u>turbidity</u> from 2007-2011
  - **Period 2**: DWTP could reduce treatment costs by lowering <u>TOC and pH</u> in source water from 2013-2015
    - Cost function better linked to algae problem

In line Turbidimeter on Raw Water Feed at DWTP

Conclusions (Cont.)

- Periods 1 and 2 revealed no cost incentive to purchase abatement
  - Other DWTPs may have incentive dependent on physiographic setting
  - Statistical model linking watershed to source WQ does not best reflect ecological knowledge
- Limitations:
  - DWTP over-treats due to uncertainties in lake ecology/water quality; hides the impact
  - Not having **appropriate** data for modeling obscures understanding of incentives
  - Linkage between watershed loads and drinking water treatability requires more consideration
  - Waiting for 2017 data to increase time series

Supplementary Material

Acknowledgments

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  - Tim Neyer
  - Mark Day

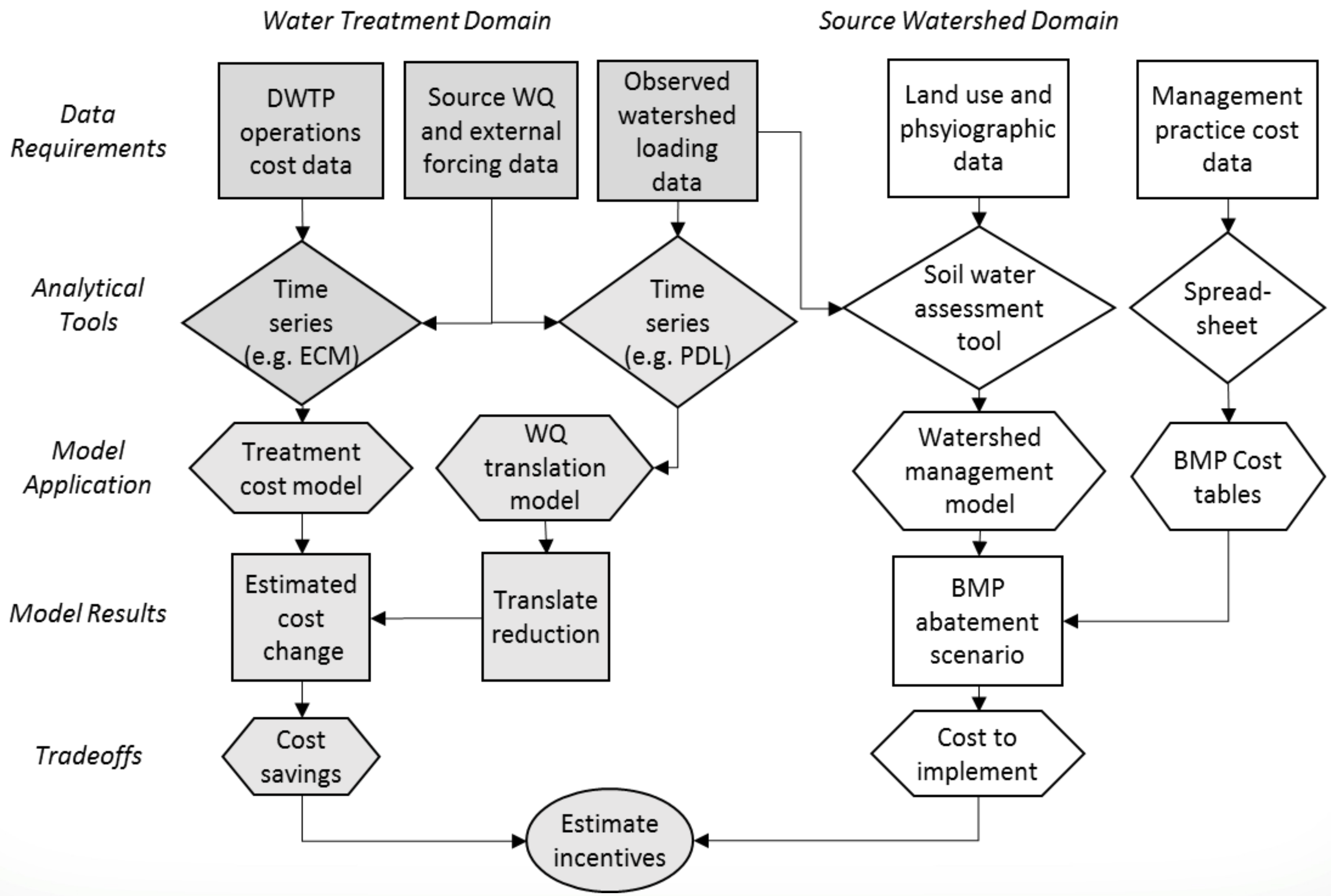
References

- Gartner, T., J. Mulligan, R. Schmidt, J. Gunn (2013), Natural Infrastructure: Investing in Forested Landscapes for Source Water Protection in the United States, World Resources Institute, Washington, DC.
- Heberling, M., C. Nietch, H. Thurston, M. Elovitz, K. Birkenhauer, S. Panguluri, B. Ramakrishnan, E. Heiser, T. Neyer (2015), Comparing Drinking Water Treatment Costs to Source Water Protection Costs Using Time Series Analysis. Water Resources Research 51:8741–8756, doi:10.1002/2014WR016422.

Background

- Concerns about water quality and drinking water safety, especially watershed nutrient loads
- Understanding how treatment costs are affected by changes in source water quality is essential to understanding tradeoffs between source water protection and treatment on site
  - Can provide evidence whether it is less expensive to invest in natural infrastructure than to pay for treatment on site
  - **Important knowledge gap for municipalities and DWTPs** (Gartner et al. 2013)

Framework


Water Treatment Domain
Source Watershed Domain
Data Requirements
Analytical Tools
Model Application
Model Results
Tradeoffs
DWTP operations cost data
Source WQ and external forcing data
Observed watershed loading data
Land use and physiographic data
Management practice cost data
Time series (e.g. ECM)
Time series (e.g. PDL)
Soil water assessment tool
Spread-sheet
Treatment cost model
WQ translation model
Watershed management model
BMP Cost tables
Estimated cost change
Translate reduction
BMP abatement scenario
Cost savings
Cost to implement
Estimate incentives

ECM equation and PDL equation

$$\Delta COST_t = \alpha_0 + \sum_{i=1}^{p-1} \alpha_i \Delta COST_{t-i} + \sum_{j=1}^{n} \sum_{i=0}^{q-1} \beta_{ji} \Delta X_{jt-i} + \alpha_p \left[COST_{t-p} - \sum_{j=1}^{n} \omega_j X_{jt-q} \right] + \varepsilon_t \quad (1)$$

$$\ln TOC_t = \alpha_0 + \beta_0 * GCPOOL_t + \beta_1 * SPR + \beta_2 * SUM + \beta_3 * CY09 + \beta_4 * CY10 + \beta_5 * CY11 + \beta_6 * CY12 + \sum_{i=0}^{v} \theta_i \ln TPLOAD_{t-i} + u_t \quad (2)$$

$$\theta_i = \alpha_0 + \sum_{j=1}^{d} \alpha_j f_j(i)$$

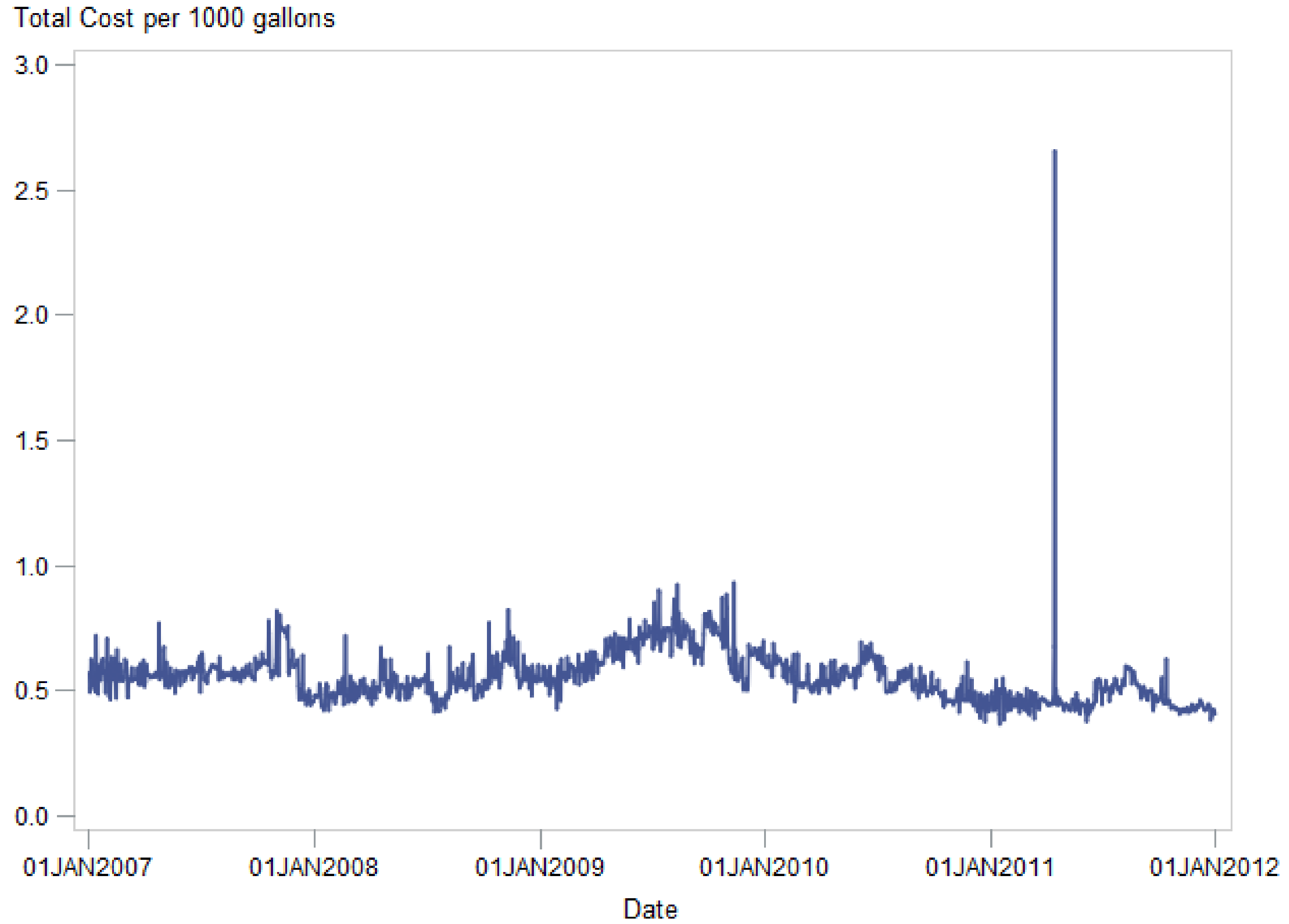
Time Series Model

- Analyze daily costs using Error Correction Model (ECM).
    - Several commonly used time series models ignore the long-run equilibrium relationships predicted by economic theory
    - Long-run and short-run effects
- Changes in one independent variable can have immediate effect on treatment costs, a long-run effect, or both.

- **Period 1**

$$\frac{Cost}{1000\ gallons} = f\begin{pmatrix} FINAL, RAWTOC, TURB, pH, \\ GCPOOL, \\ TEMP, ActualTOC, \\ SPRSUM, CY07 - CY10, PROCESS \end{pmatrix}$$

Total Cost per 1000 Gallons of Finished Flow (Aug 2012$)



ECM Results, Period 1

- Cost of treating turbid water depends on current turbidity and water previously treated

- 1% decrease in TURB(≈ 0.11NTU) leads to an immediate decrease of 0.02% in TC/1000 gal. with another 0.1% decrease over future time. Total effect is 0.11%

- 1% decrease in turbidity, leads to $1120 annual decrease in treatment costs

Link Water Quality to Load Reductions

- How does total phosphorus (TP) load impact turbidity in source (raw) water?
  - Chose TP load because its affinity for natural clay particles and its link to harmful algal blooms
  - Ideal: Link daily nutrient/sediment results to daily turbidity (TURB)
  - TP load is weekly measurement of daily grab sample

- **Period 1**: Time series analysis (polynomial distributed lag model)
  - TURB=f(TPLOAD, GCPOOL, SPR, CY09, CY10)

- 1% reduction in TPLOAD (≈ 10.74 lbs/day) leads to 0.15% decrease in turbidity over the long-run (5 weeks)
  - $168 in treatment cost savings from 1% annual reduction in TP load
  - Cost to control 10.74 lbs/day for a year using cover crops = $11763--$105867
  - Price/lb = $3—$27; 10.74*365*price

ECM results, Period 2

GARCH Estimates

SSE	12.2817467	Observations	1093
MSE	0.01124	Uncond Var	0.01109977
Log Likelihood	1313.45428	Total R-Square	0.9213
SBC	-2458.9882	AIC	-2578.9086
MAE	0.05345213	AICC	-2577.785
MAPE	271.364121	HQC	-2533.5276
		Normality Test	7880.6867
		Pr > ChiSq	<.0001

Parameter Estimates

Variable	*DF*	*Estimate*	*Standard Error*	*t Value*	*Approx Pr > |t|*
Intercept	1	0.4533	0.1704	2.66	0.0078
l_finaldiff	1	-0.7690	0.0886	-8.68	<.0001
l_rawtocdiff	1	0.1348	0.0748	1.80	0.0716
turbdiff	1	-0.000989	0.000429	-2.31	0.0211
phdiff	1	0.002229	0.0189	0.12	0.9061
p_sdiff	1	0.001056	0.001985	0.53	0.5948
tocdumdiff	1	0.001898	0.006447	0.29	0.7684
AOsep2013diff	1	0.6069	0.2710	2.24	0.0251
AO2015_2diff	1	0.8774	0.1912	4.59	<.0001
ll_total1realdiff	1	-0.1886	0.0330	-5.71	<.0001
ll2_total1real	1	-0.0642	0.0206	-3.12	0.0018
ll_final	1	-0.0896	0.0262	-3.43	0.0006
ll_rawtoc	1	0.0362	0.0304	1.19	0.2340
lag_turb	1	-0.001033	0.000632	-1.64	0.1020
lag_ph	1	0.0249	0.009419	2.64	0.0083
lag_ps	1	0.000694	0.000921	0.75	0.4510
lag_qtr2	1	0.0156	0.006682	2.33	0.0197
lag_tocdum	1	0.0106	0.009790	1.09	0.2777
lag_cy13	1	0.009214	0.0132	0.70	0.4842
lag_cy14	1	-0.004058	0.004439	-0.91	0.3606
lag_AOsep2013	1	0.4137	0.2155	1.92	0.0549
lag_AO2015_2	1	1.3004	0.4946	2.63	0.0086
ARCH0	1	0.003265	0.000645	5.06	<.0001
ARCH1	1	0.7058	0.3127	2.26	0.0240

PDL results, Period 2

Estimate of Lag Distribution											
Variable	Estimate	Standard	t Value	Approx	0 314E-7						
		Error		Pr > |t|							
tploadlb(0)	0.00000152	9.26E-06	0.16	0.8698	|** |						
tploadlb(1)	0.000008634	8.14E-06	1.06	0.2898	|*********** |						
tploadlb(2)	0.000014784	8.74E-06	1.69	0.092	|******************* |						
tploadlb(3)	0.000019969	9.73E-06	2.05	0.0413	|************************** |						
tploadlb(4)	0.00002419	0.0000103	2.34	0.0203	|******************************** |						
tploadlb(5)	0.000027446	0.0000103	2.66	0.0084	|************************************ |						
tploadlb(6)	0.000029738	9.69E-06	3.07	0.0024	|*************************************** |						
tploadlb(7)	0.000031066	8.73E-06	3.56	0.0004	|***|						
tploadlb(8)	0.000031429	8.29E-06	3.79	0.0002	|***|						
tploadlb(9)	0.000030827	9.68E-06	3.18	0.0016	|** |						
Convert to elasticity		RAWTOC									
tploadlb(0)	0.00000152	0									
tploadlb(1)	0.000008634	0				Cost MGD	Cost day	Cost year	1% RAWTOC 0.1348% TC		
tploadlb(2)	0.000014784	0.002650673				810	2745.9	1002254	1351.038		
tploadlb(3)	0.000019969	0.003580309							29270.95	L-R pH cost	
tploadlb(4)	0.00002419	0.004337107							1%TPLOAD		
tploadlb(5)	0.000027446	0.004920886							0.507353		
tploadlb(6)	0.000029738	0.005331826									
tploadlb(7)	0.000031066	0.005569928									
tploadlb(8)	0.000031429	0.005635011									
tploadlb(9)	0.000030827	0.005527077									
		0.037552817									