Minimum Detectable Change

Selecting Appropriate Sample Sizes for Watershed Programs

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Presentation Outline

- Monitoring Design Options
- Sampling Frequency Issues
  - Autocorrelation
- Mean/median estimation
  - Basic Equations
- Trend Detection
  - Introduction
    - Minimum detectable change (MDC)
    - Type I and II error
    - Power
  - Step Trends (2-sample tests)
  - Paired Tests ("Repeated Observation")
  - Paired Watershed

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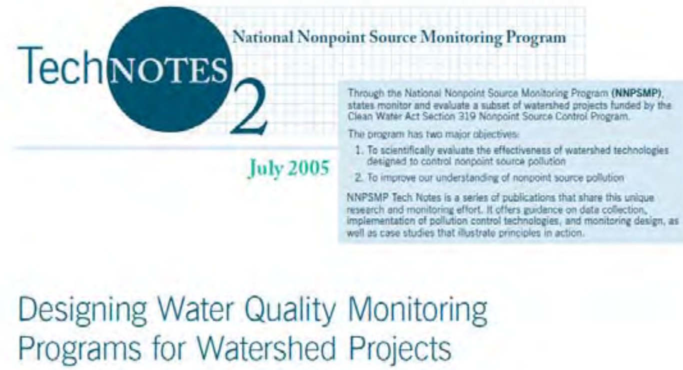
Monitoring Design Selection



TechNOTES 2

National Nonpoint Source Monitoring Program

July 2005

Through the National Nonpoint Source Monitoring Program **(NNPSMP)**, states monitor and evaluate a subset of watershed projects funded by the Clean Water Act Section 319 Nonpoint Source Control Program.

The program has two major objectives:

1. To scientifically evaluate the effectiveness of watershed technologies designed to control nonpoint source pollution
2. To improve our understanding of nonpoint source pollution

NNPSMP Tech Notes is a series of publications that share this unique research and monitoring effort. It offers guidance on data collection, implementation of pollution control technologies, and monitoring design, as well as case studies that illustrate principles in action.

Designing Water Quality Monitoring Programs for Watershed Projects

- Monitoring objectives drive decisions on the details of a monitoring program
- Multiple experimental designs can be applied to meet monitoring objectives
- Selection should be based on
  - Available resources
  - Fewest logistical obstacles
  - Although obvious, monitoring design should be determined before monitoring begins to ensure that suitable data are collected to meet monitoring objectives

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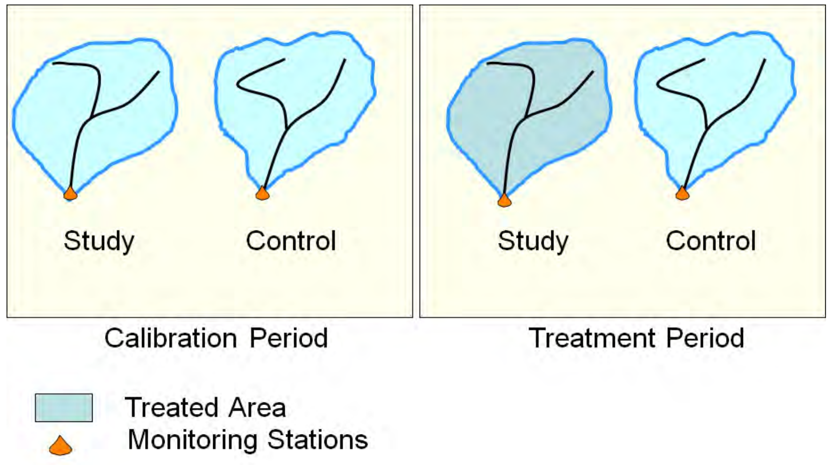
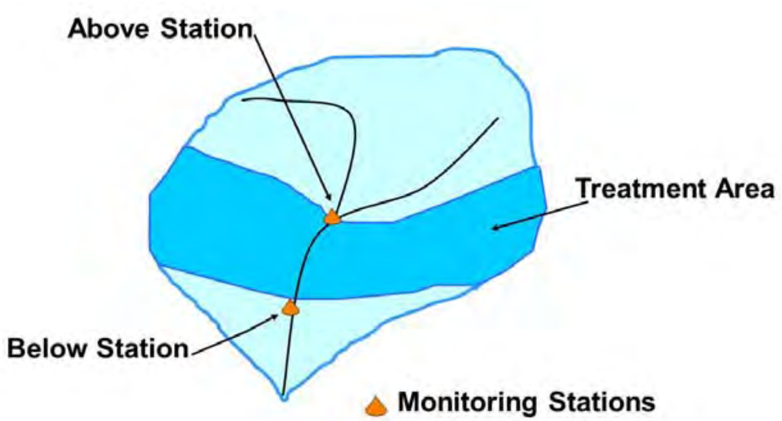
Design Options

- Paired-watershed design
  - Most powerful design option for evaluating impact of BMPs or projects
- Above/Below
  - <u>Nested, paired-watershed</u> approach if before and after BMP implementation is monitored

Paired-watershed design



Above/Below



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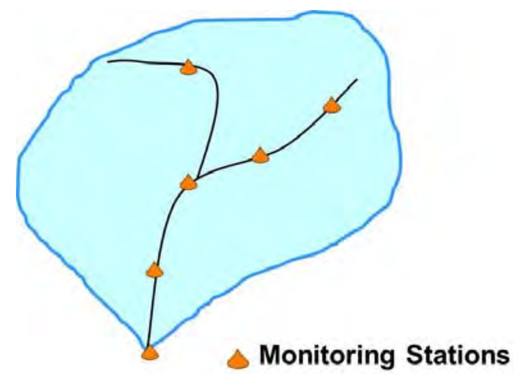
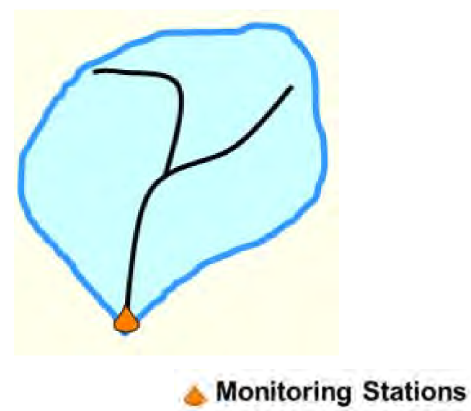
Design Options

- Reconnaissance or synoptic studies
  - Determine the magnitude and extent of a problem
  - Obtain preliminary data where none exist
  - Target critical areas
- Single-station long-term trend
- Single watershed before/after
  - May be used to measure pollutant loads before and after implementation of the TMDL
  - Typically expect to detect step changes
  - Confounding factors (e.g., dry vs. wet years) make isolating BMP effectiveness difficult

Reconnaissance or synoptic studies

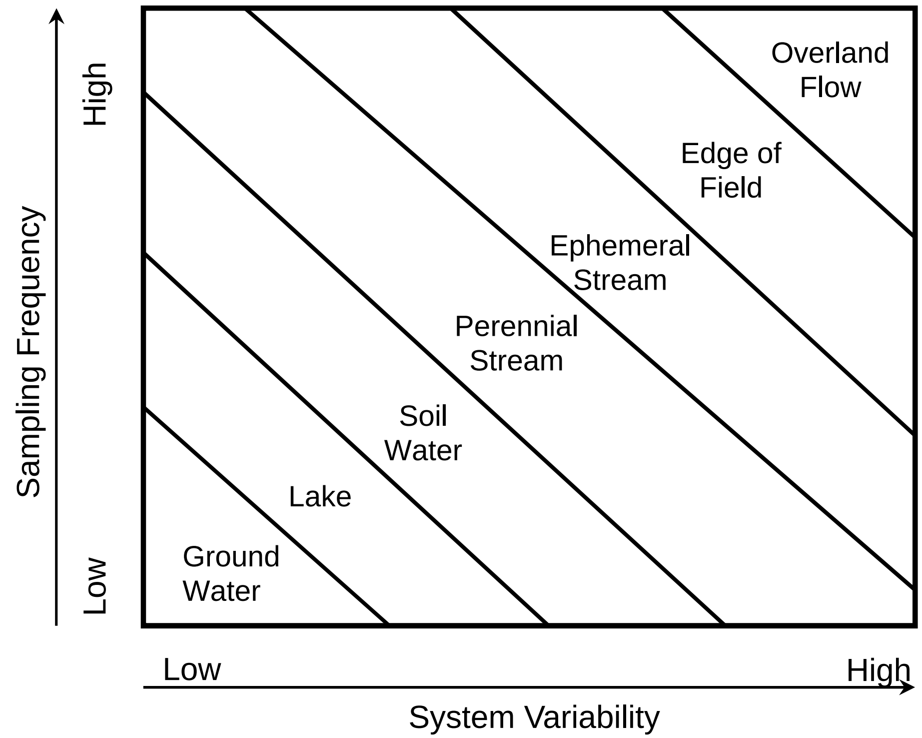


Single-station: - Long-term
- Before/After



Sampling Frequency Issues

- Appropriate sample frequency varies with the objectives of the monitoring project:
  - Estimation of the mean
  - Detection of change
  - Estimation of load*
- Required Sample Size
  - Variability
  - Sampling Frequency
- Need to plan for auto-correlation



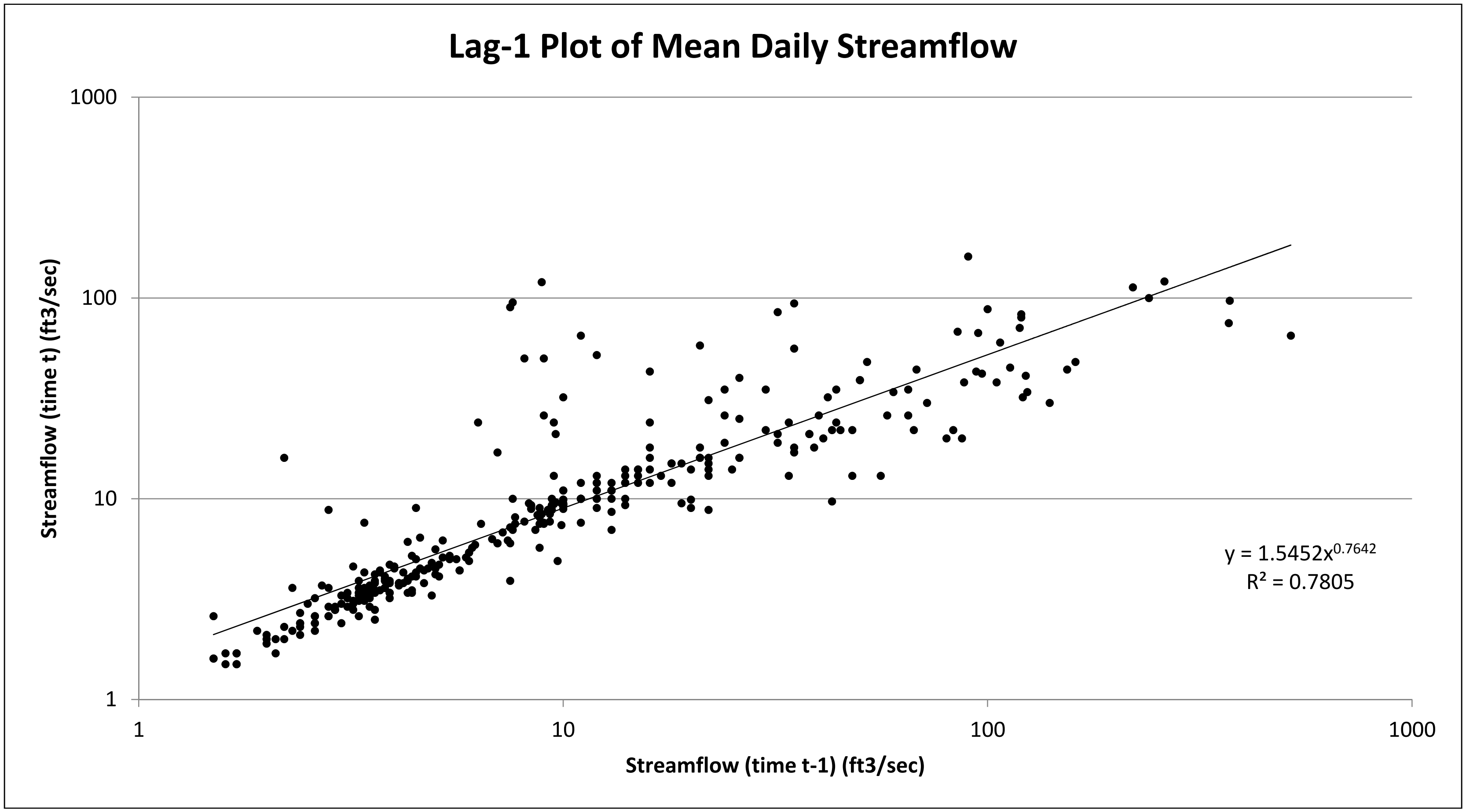
After USDA. 2003. National water quality handbook.

*http://www.epa.gov/Region5/agriculture/pdfs/nutrient2014/webinar-20141217.pdf

Autocorrelation

- With autocorrelation, subsequent samples
  - Are influenced by previous samples
  - Contain less new information
  - Reduces *effective* sample size
- **Autocorrelation coefficient (ρ)**
  - **ρ** increases as the strength of the relationship between current and past samples increases.
  - Larger **ρ** means that each collected sample has less new information
  - Relative improvement in estimates of a mean or a minimum detectable change decreases as sample size increases.

Autocorrelation in Flow



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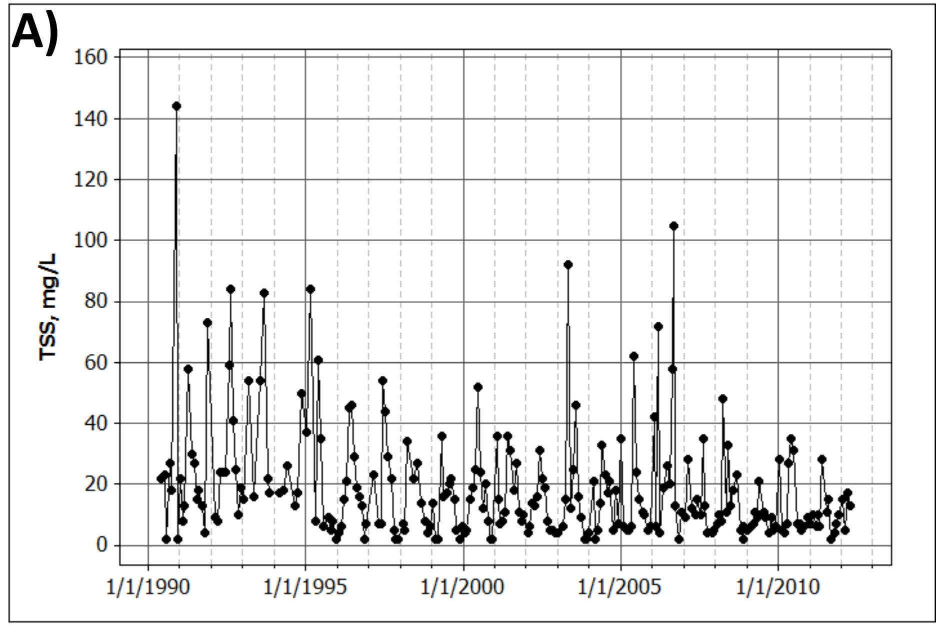
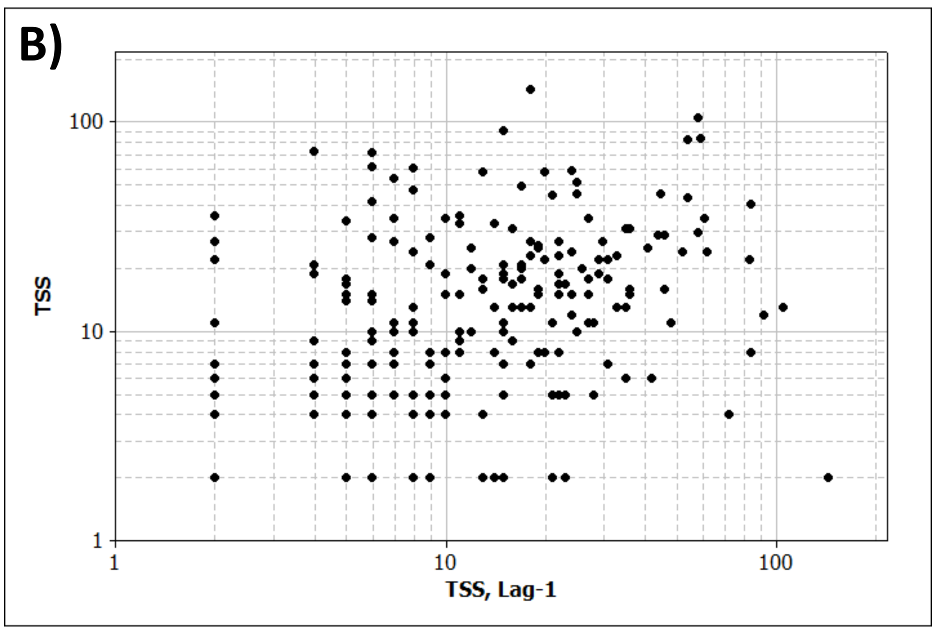
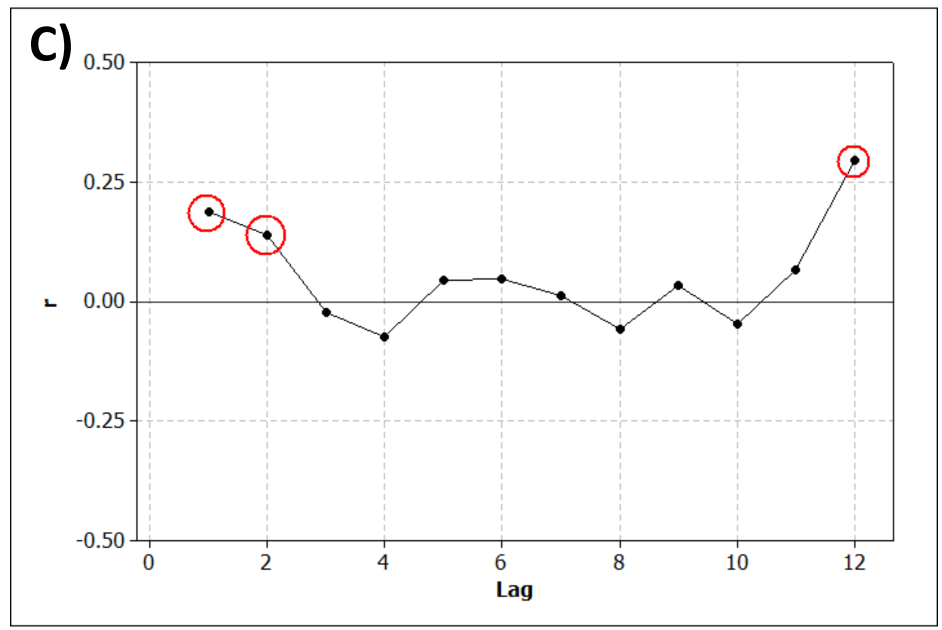
Autocorrelation in TSS

- Monthly 1990-2012 TSS from Little Calumet East Branch
- Mean: 18.7, StDev: 19.4
- $C_v = 1.0$
- Lag-1 correlation = 0.19





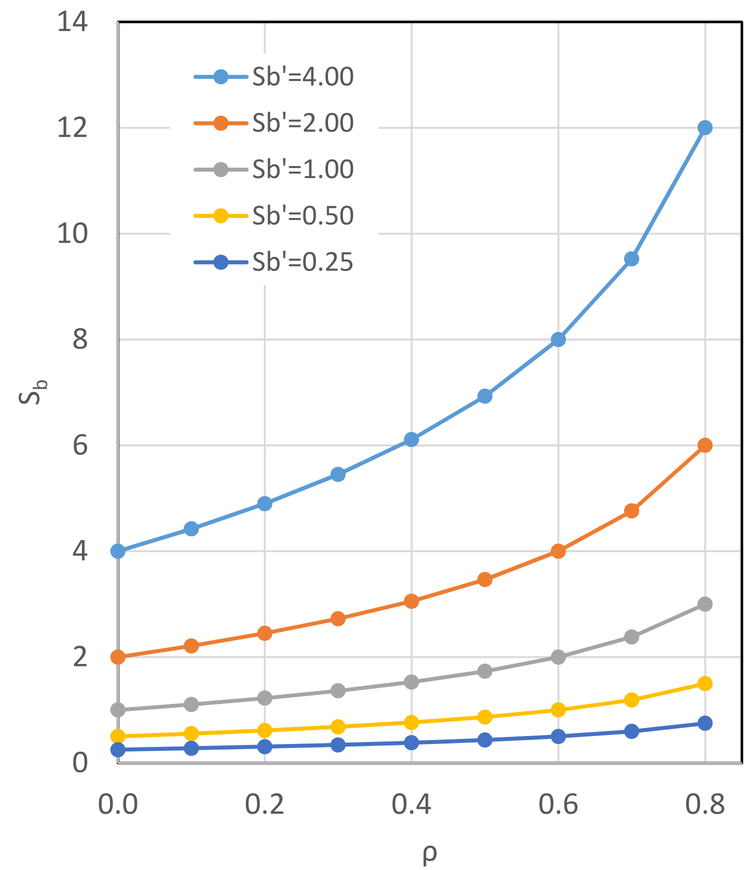


Autocorrelation

Adjust standard deviation with the following large sample approximation:

$$s_b = s_b' \sqrt{\frac{1+\rho}{1-\rho}}$$

ρ = autocorrelation coefficient for autoregressive lag 1, AR(1)



ρ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
S_b/S_b'	1.11	1.22	1.36	1.53	1.73	2.00	2.38	3.00

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Summary Statistics

- Estimates of mean, median, and geometric mean are basic statistics that are often used
- Helpful to develop precision statements with these basic statistics as a step toward more challenging MDC calculations

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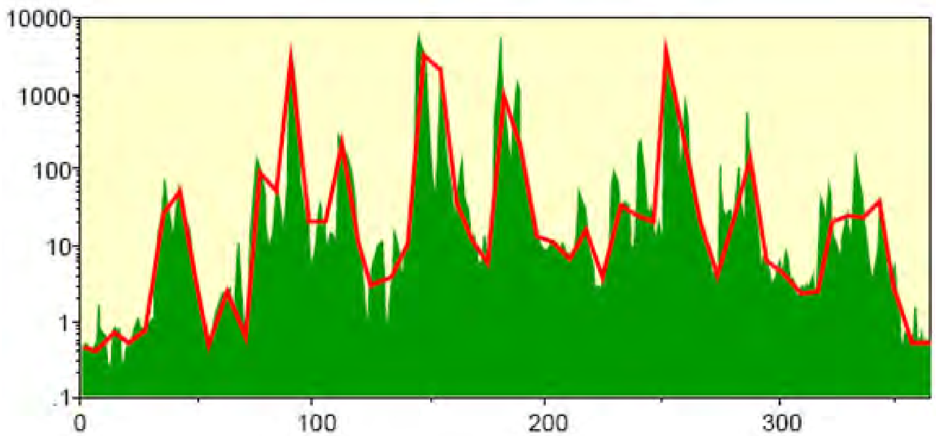
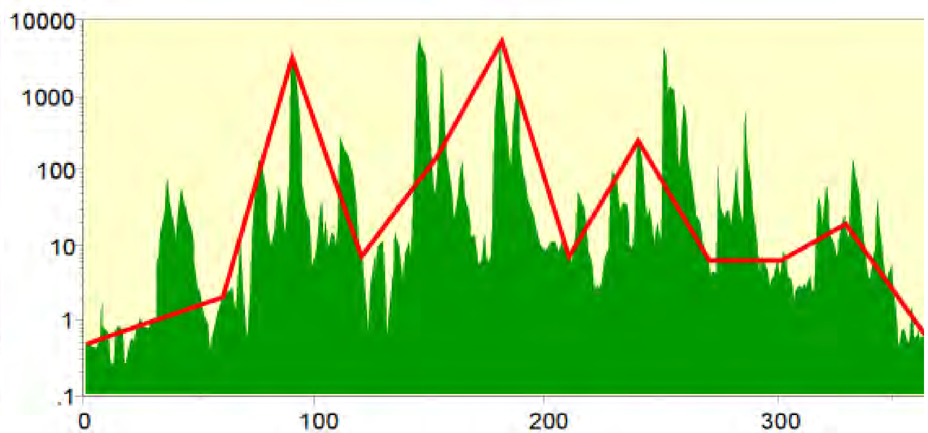
Mean Estimation

- Determine the sampling frequency necessary to obtain an estimate of the mean for a water quality variable with a certain amount of confidence.
- Example assumes analysis is for problem assessment and samples are evenly spaced over time.





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Mean Estimation

Question	Large N	Finite N
What sample size is required to estimate the mean within ±5 mg/L (i.e., d=5)?	$n = (t \cdot s/d)^2$	$n = \dfrac{(t \cdot s/d)^2}{1 + (t \cdot s/d)^2/N}$
What sample size is required to estimate the mean within ±15% (i.e., d_r=0.15)?	$n = (t \cdot C_v/d_r)^2$	$n = \dfrac{(t \cdot C_v/d_r)^2}{1 + (t \cdot C_v/d_r)^2/N}$

t = 2-tailed Student's t with n-1 degrees of freedom and specified confidence level. Excel formula: =T.INV.2T(α,n-1)

s = estimate of the population standard deviation

C_v = coefficient of variation ($C_v = s/\bar{x}$)

d = allowable error ($d = d_r \cdot \bar{x}$)

d_r = relative error

Mean Estimation

- How many samples are needed to be within ±10 and ±20 percent of the true annual mean TP concentration at the 95% confidence level?
- Existing data tell us:
  - Mean = 0.83 mg/L
  - Standard deviation, s = 0.62 mg/L
  - C_v = 0.62/0.83 = 0.75
  - d_r = 0.10 & 0.20
  - α=0.05
- Apply

$$n = (t \cdot C_v / d_r)^2$$

For a ±10% estimate (α=0.05):

$$n = \left(\frac{1.97 \times 0.75}{0.10}\right)^2 = \underline{\mathbf{219}}$$

For a ±20% estimate (α=0.05):

$$n = \left(\frac{2.00 \times 0.75}{0.20}\right)^2 = \underline{\mathbf{57}}$$

1. *Check t-value for computed n to see if iterative calculation is needed.*
2. *219 samples/yr → autocorrelation* (reduces effective sample size).
3. α=0.10 → 155 and 40 samples, respectively

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Mean Estimation

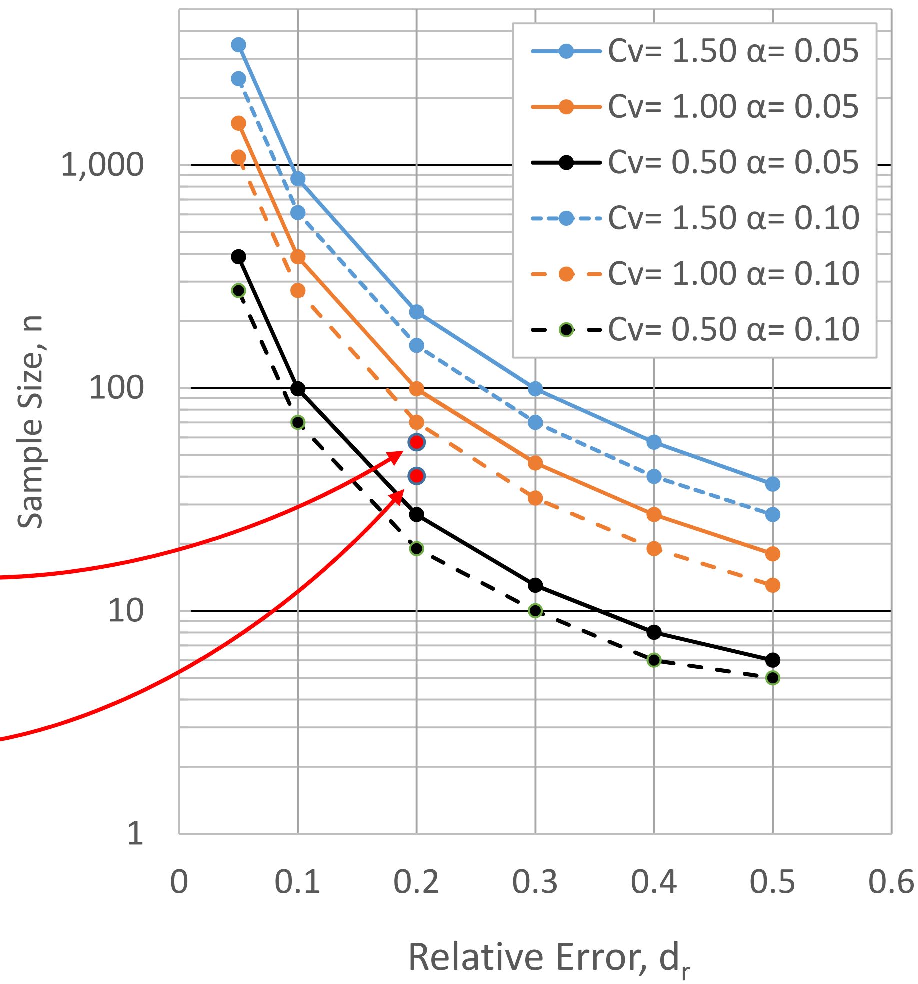
- Sample size calculations
  - C_v = 1.50, 1.00, and 0.50
  - α = 0.05 & 0.10

For a ±20% estimate (α=0.05):

$$n = \left(\frac{2.00 \times 0.75}{0.20}\right)^2 = \underline{\mathbf{57}}$$

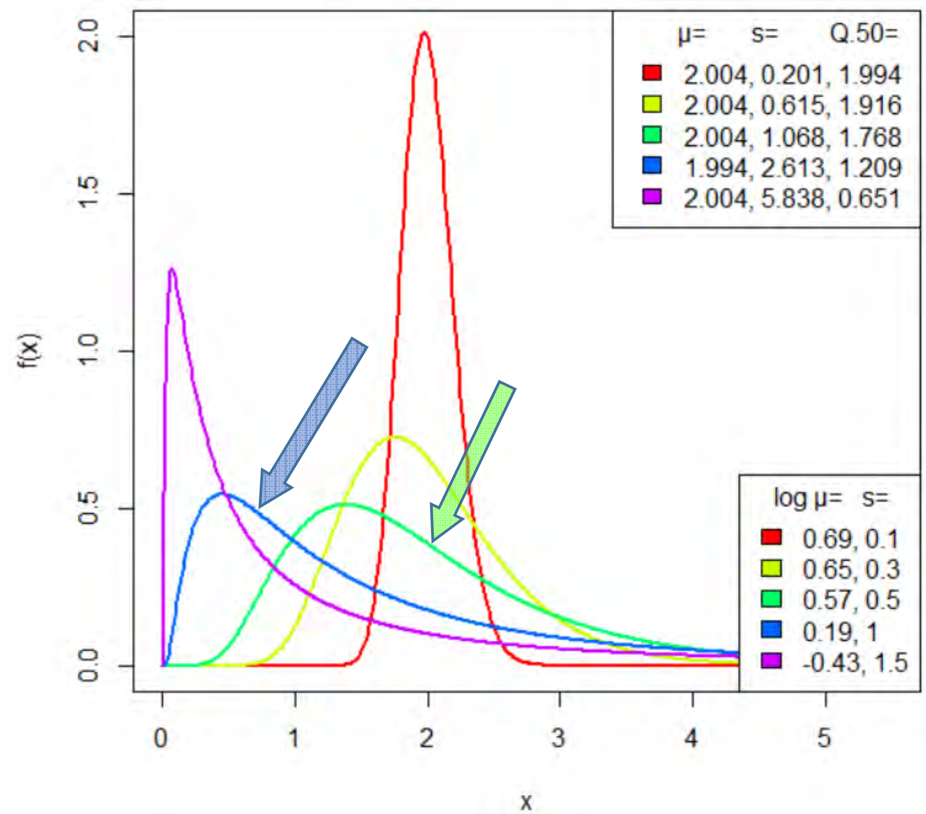
For a ±20% estimate (α=0.10):

$$n = \left(\frac{1.684 \times 0.75}{0.20}\right)^2 = \underline{\mathbf{40}}$$



Median vs. Geometric Mean

- Geometric Mean is more efficient* if data are truly lognormal
- Median is more efficient if data are still somewhat skewed after log transformation
- All of the lognormal distributions to the right have a mean of 2 in untransformed units.



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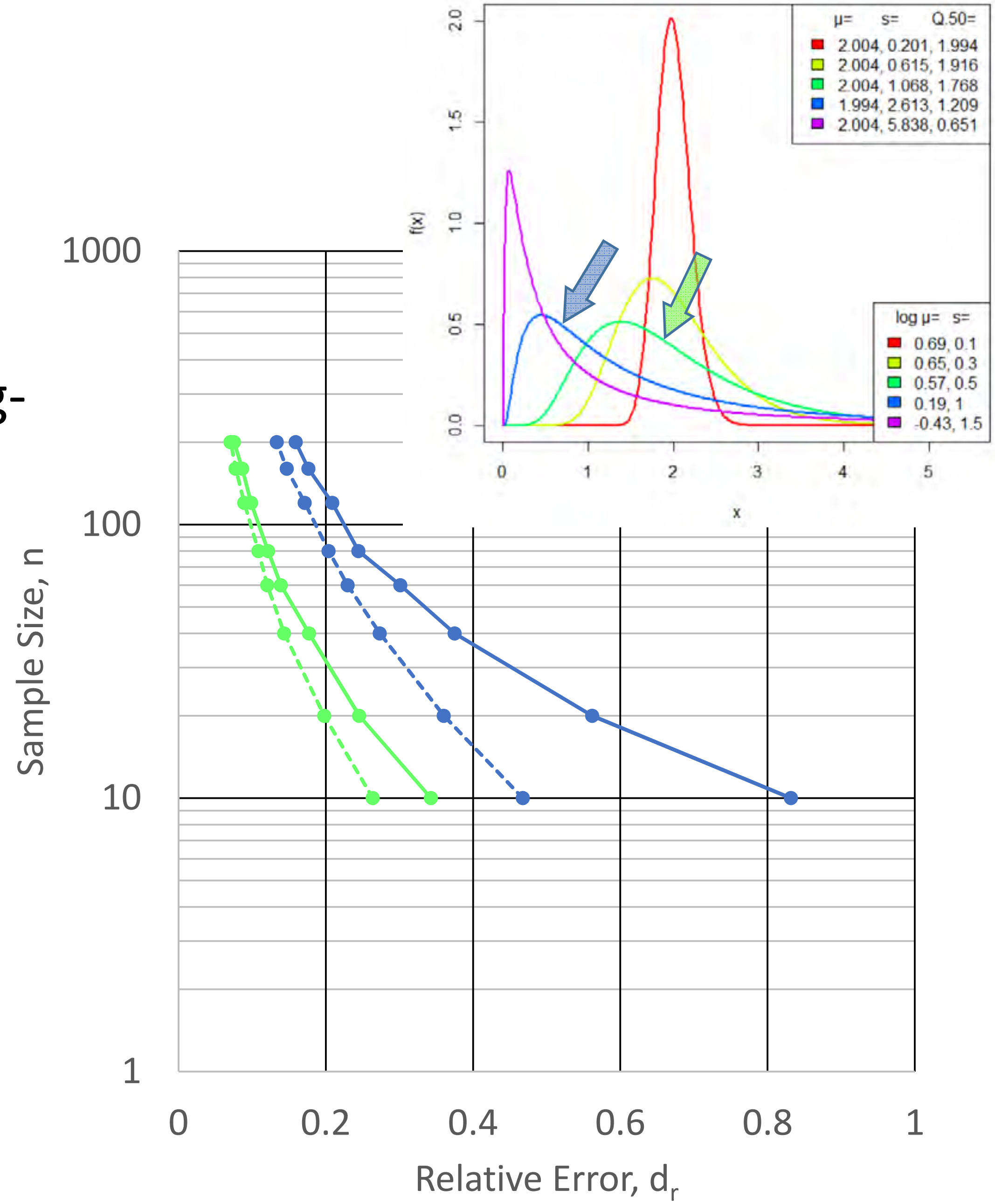
*Smaller confidence interval

Sample Size Estimation

Geometric mean is similar to mean except work in log-transformed units

- $n = \left(t \cdot s_y / d_y\right)^2$
- Confidence interval is asymmetric

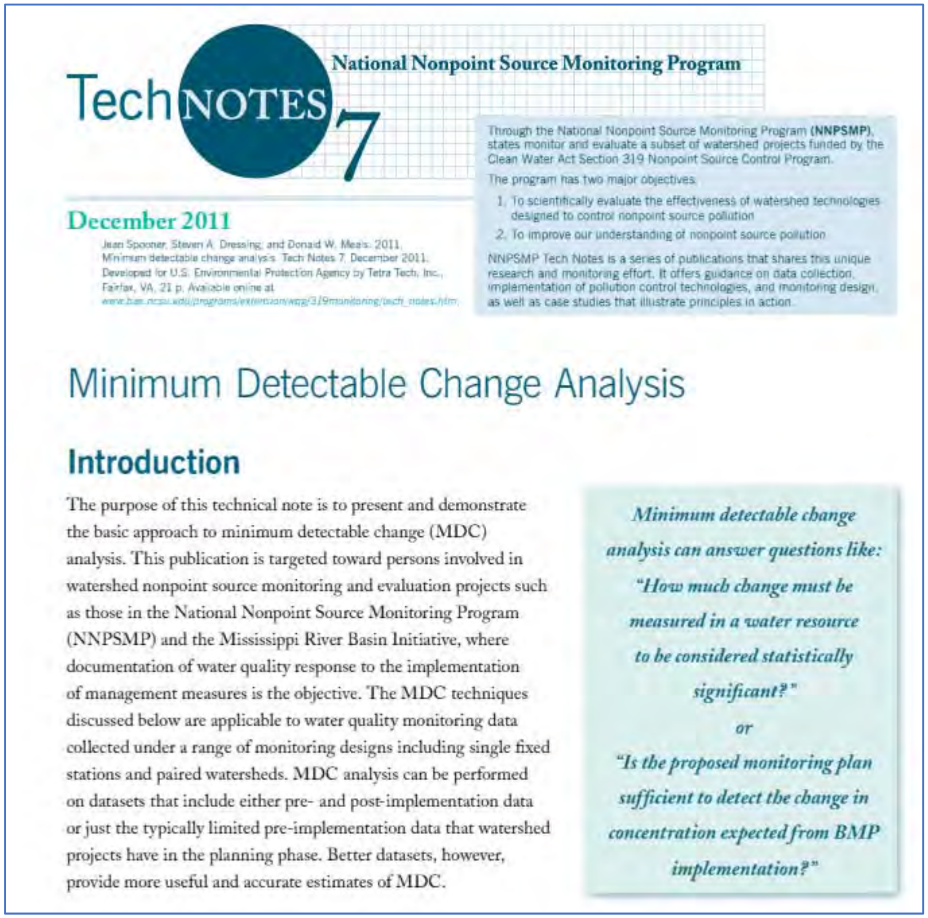


Trend Detection

- Introduction
  - Minimum detectable change (MDC)
  - Type I and II error
  - Power
- Step Trends (2-sample tests)
- Paired Tests (“Repeated Observation”)
- Paired Watershed

Minimum Detectable Change (MDC)

"The minimum change in a pollutant concentration (or load) during a given time period required for the change to be considered statistically significant"



Tech NOTES 7

National Nonpoint Source Monitoring Program

December 2011

Jean Spooner, Steven A. Dressing, and Donald W. Meals. 2011. Minimum detectable change analysis. Tech Notes 7, December 2011. Developed for U.S. Environmental Protection Agency by Tetra Tech, Inc., Fairfax, VA, 21 p. Available online at www.bae.ncsu.edu/programs/extension/wqg/319monitoring/tech_notes.htm.

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Minimum Detectable Change Analysis

Introduction

The purpose of this technical note is to present and demonstrate the basic approach to minimum detectable change (MDC) analysis. This publication is targeted toward persons involved in watershed nonpoint source monitoring and evaluation projects such as those in the National Nonpoint Source Monitoring Program (NNPSMP) and the Mississippi River Basin Initiative, where documentation of water quality response to the implementation of management measures is the objective. The MDC techniques discussed below are applicable to water quality monitoring data collected under a range of monitoring designs including single fixed stations and paired watersheds. MDC analysis can be performed on datasets that include either pre- and post-implementation data or just the typically limited pre-implementation data that watershed projects have in the planning phase. Better datasets, however, provide more useful and accurate estimates of MDC.

Minimum detectable change analysis can answer questions like: "How much change must be measured in a water resource to be considered statistically significant?"

or

"Is the proposed monitoring plan sufficient to detect the change in concentration expected from BMP implementation?"

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Minimum Detectable Change Steps

1. Define the Monitoring Goal and Choose the Appropriate Statistical Trend Test Approach
2. Exploratory Data Analyses
3. Data Transformations
4. Test for Autocorrelation
5. Calculate the Estimated Standard Error
6. Calculate the MDC
7. Express MDC as a Percent Change

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Definitions

- Null Hypothesis (H_o)
  - Traditionally, H_o is a statement of no change, no effect, or no difference, e.g.,
  - "the average TN concentration after the cost-share program is equal to the average TN concentration before the cost-share program"
- Alternative Hypothesis (H_a)
  - Counter to H_o, traditionally being a statement of change, effect, or difference

Errors in Hypothesis Testing

- Type I error: H_o is rejected when H_o is really true
- Type II error: H_o is accepted when H_o is really false

Decision	State of Affairs in the Population	
	H_o is True	H_o is False
Accept H_o	1-α (Confidence level)	β (Type II error)
Reject H_o	α (Significance level) (Type I error)	1-β (Power)

- *Power (1-β):* Probability of correctly rejecting H_o when H_o is false

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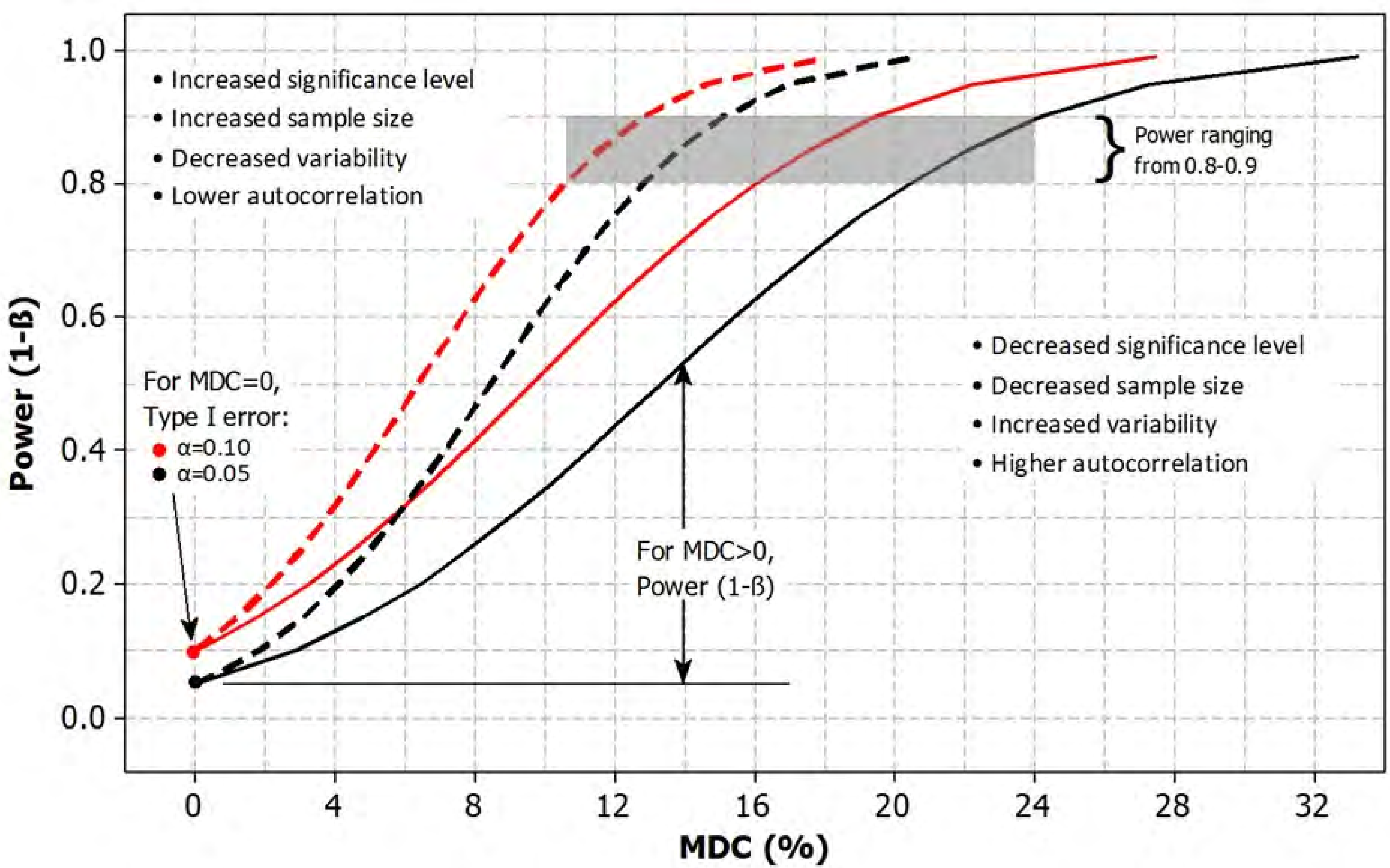
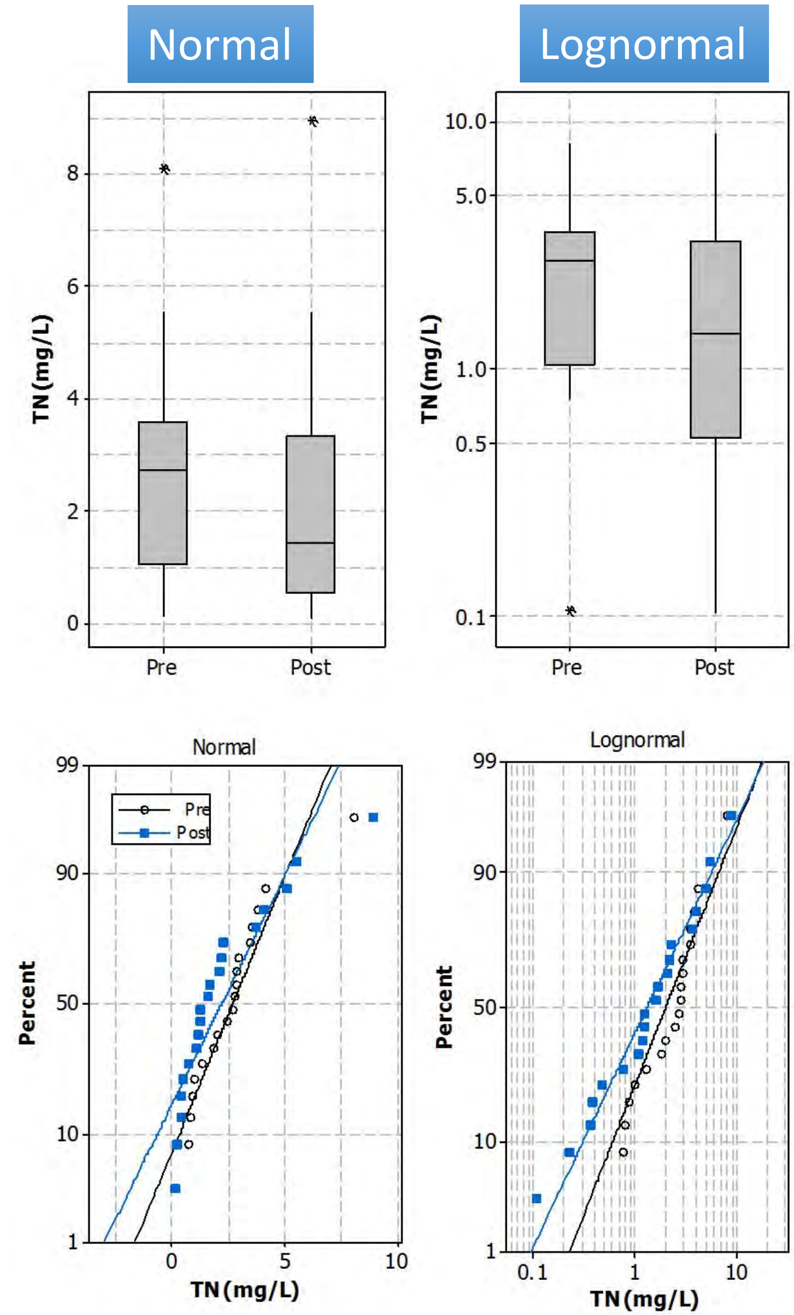
Power Curve


1.0
0.8
0.6
0.4
0.2
0.0
Power (1-ß)
• Increased significance level
• Increased sample size
• Decreased variability
• Lower autocorrelation
Power ranging from 0.8-0.9
• Decreased significance level
• Decreased sample size
• Increased variability
• Higher autocorrelation
For MDC=0,
Type I error:
α=0.10
α=0.05
For MDC>0,
Power (1-ß)
0
4
8
12
16
20
24
28
32
MDC (%)

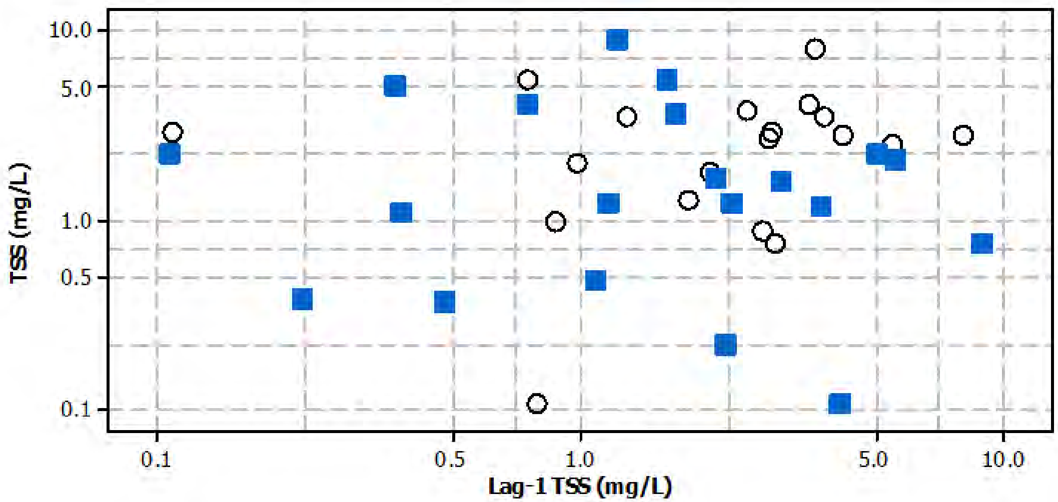
Example 1: TN

1. Monitoring Objective
    - Bimonthly grab sampling at a single site
    - 20 samples pre- and 20 samples post-BMP implementation
    - H_o: No change in TN
    - H_a: TN decreased after BMP implementation
    - Two-sample test
2. Data Exploration
    - Distribution → Lognormal
    - Variance: F Test=0.68 → p=0.41

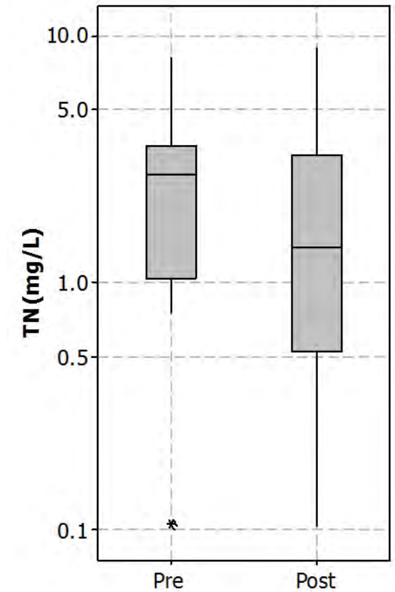


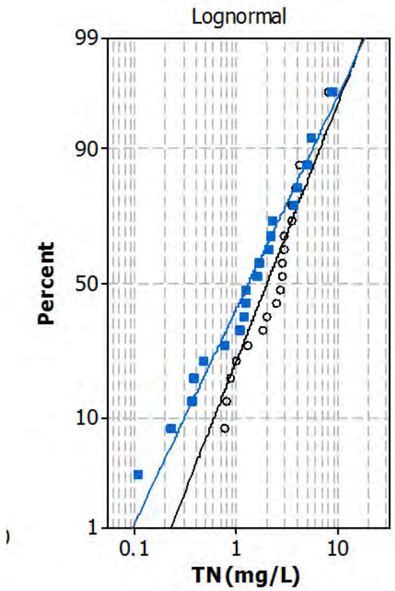
Example 1: TN (cont.)

3. Data Transformations
   - y = log10 (TN)
4. Test for Autocorrelation
   - Pearson correlation: 0.053 → p=0.751
     $\log10(TN)_i$ vs. $\log10(TN)_{i-1}$



Lognormal





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Example 1: TN (cont.)

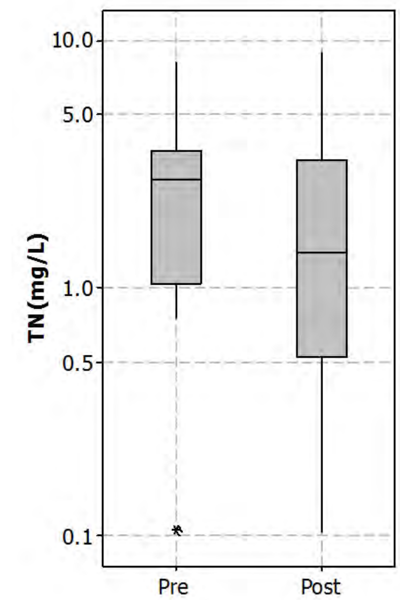
5. Calculate the Estimated Standard Error

One-way ANOVA: Log10_Trtmt versus Period

```
Source  DF     SS     MS     F      P
Period   1  0.333  0.333  1.60  0.214 ← NOT STATISTICALLY DIFFERENT

Error   38  7.928  0.209 ← MEAN SQUARED ERROR
Total   39  8.261

S = 0.4567   R-Sq = 4.03%   R-Sq(adj) = 1.51%
```

Two-sample T for Log10_Trtmt

```
Period   N   Mean  StDev  SE Mean
0       20  0.301  0.411    0.092
1       20  0.118  0.498     0.11

Difference = mu (0) - mu (1)
Estimate for difference:  0.182
95% lower bound for difference:  -0.061
T-Test of difference = 0 (vs >): T-Value = 1.26  P-Value = 0.107  DF = 36
```



Accommodations

- MSE—unlikely to have
  - Use variance of Pre-BMP data, $s_{pre}^2 = MSE$
- Autocorrelation if using OLS (i.e., Pearson corr. coeff.)

$$s_b = s_b' \sqrt{\frac{1+\rho}{1-\rho}}$$

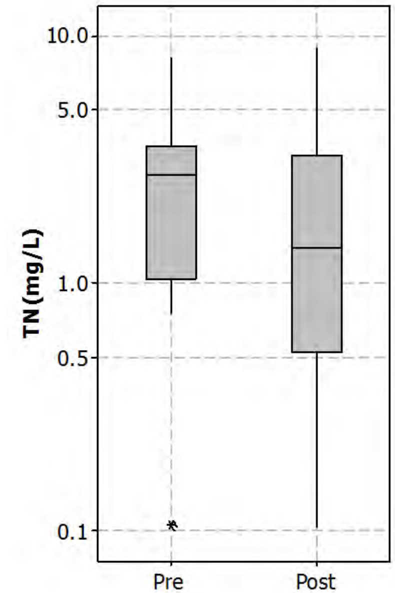
- Change in Post-BMP variance—use pooled variance

$$s_p^2 = \frac{(n_{pre}-1)s_{pre}^2 + (n_{post}-1)s_{post}^2}{(n_{pre}-1) + (n_{post}-1)}$$

Example 1: TN (cont.)

6. Calculate the MDC

$$\mathrm{MDC} = \left(t_{\alpha, n_{pre}+n_{post}-2} + t_{2\beta, n_{pre}+n_{post}-2}\right)\sqrt{\frac{\mathrm{MSE}}{n_{pre}} + \frac{\mathrm{MSE}}{n_{post}}}$$



H_O: $TN_{Pre} = TN_{Post}$
H_A: $TN_{Pre} > TN_{Post}$ → one-sided test

Confidence Level: 90%

- Type I error (sign. level, α) = 0.10

Power (1- β): 80%

- Type II error (β) = 0.20
- 2β = 0.4

$t_{\alpha, n_{pre}+n_{post}-2}$ → $t_{0.10, 36}$ → 1.304
$t_{2\beta, n_{pre}+n_{post}-2}$ → $t_{0.4, 36}$ → 0.851

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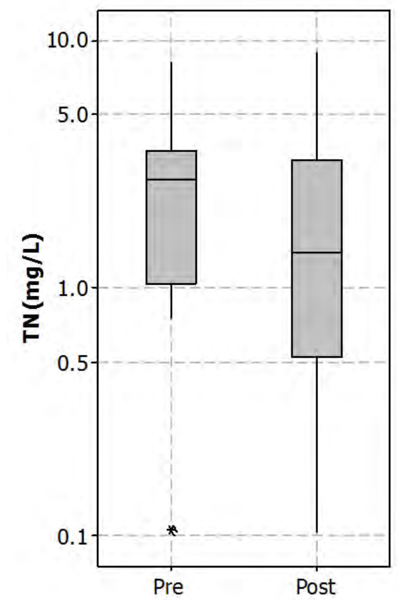
Example 1: TN (cont.)

$$\text{MDC} = \left(t_{\alpha, n_{pre}+n_{post}-2} + t_{2\beta, n_{pre}+n_{post}-2}\right)\sqrt{\frac{\text{MSE}}{n_{pre}} + \frac{\text{MSE}}{n_{post}}}$$

$$\text{MDC} = (1.304 + 0.851)\sqrt{\frac{0.209}{20} + \frac{0.209}{20}}$$ → 0.312 (log-transformed units)



7. Calculate the MDC(%)

MDC% → Raw data: MDC% = 100*(MDC/$\bar{x}_{pre}$)

→ Log-trans. MDC% = (1 – 10^{-MDC}) * 100

MDC(%) = (1-$10^{-0.312}$) *100 → **<u>51%</u>**

→ A 51% decrease in TN can be detected at the 90% confidence level with an 80% power.

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Example 2—Tech Notes 7

- One-sided, two-sample t-test
  - H_o: $\bar{x}_{pre} = \bar{x}_{post}$
  - H_a: $\bar{x}_{pre} > \bar{x}_{post}$
- Significance level (α) = 0.05
- Power (1-β) = 0.8
- ρ = 0
- $n_{pre} = n_{post}$ = 52 samples
- $\bar{x}_{pre}$ = 36.9 mg/L, pre-BMP mean
- s_{pre} = 21.2 mg/L, pre-BMP std. dev.
- MSE = s_{pre}^2 = 449.44

- $t_{\alpha,n_{pre}+n_{post}-2}$ = 1.6599
- $t_{2\beta,n_{pre}+n_{post}-2}$ = 0.8452
- MDC (for power = 0.8)

$$(1.6599 + 0.8452)\sqrt{\frac{449}{52} + \frac{449}{52}} = 10.4 \text{ mg/L}$$

  - MDC% = 100*(10.4/36.9) = 28%

  → **80% probability that a decrease of 10.4 mg/L (28%) can be detected**

- For power = 0.5, $t_{2\beta}$ = 0
  - MDC = 6.9 mg/L
  - MDC% = 100*(6.9/36.9) = 19%

  → **50% probability that a decrease of 6.9 mg/L (19%) can be detected**

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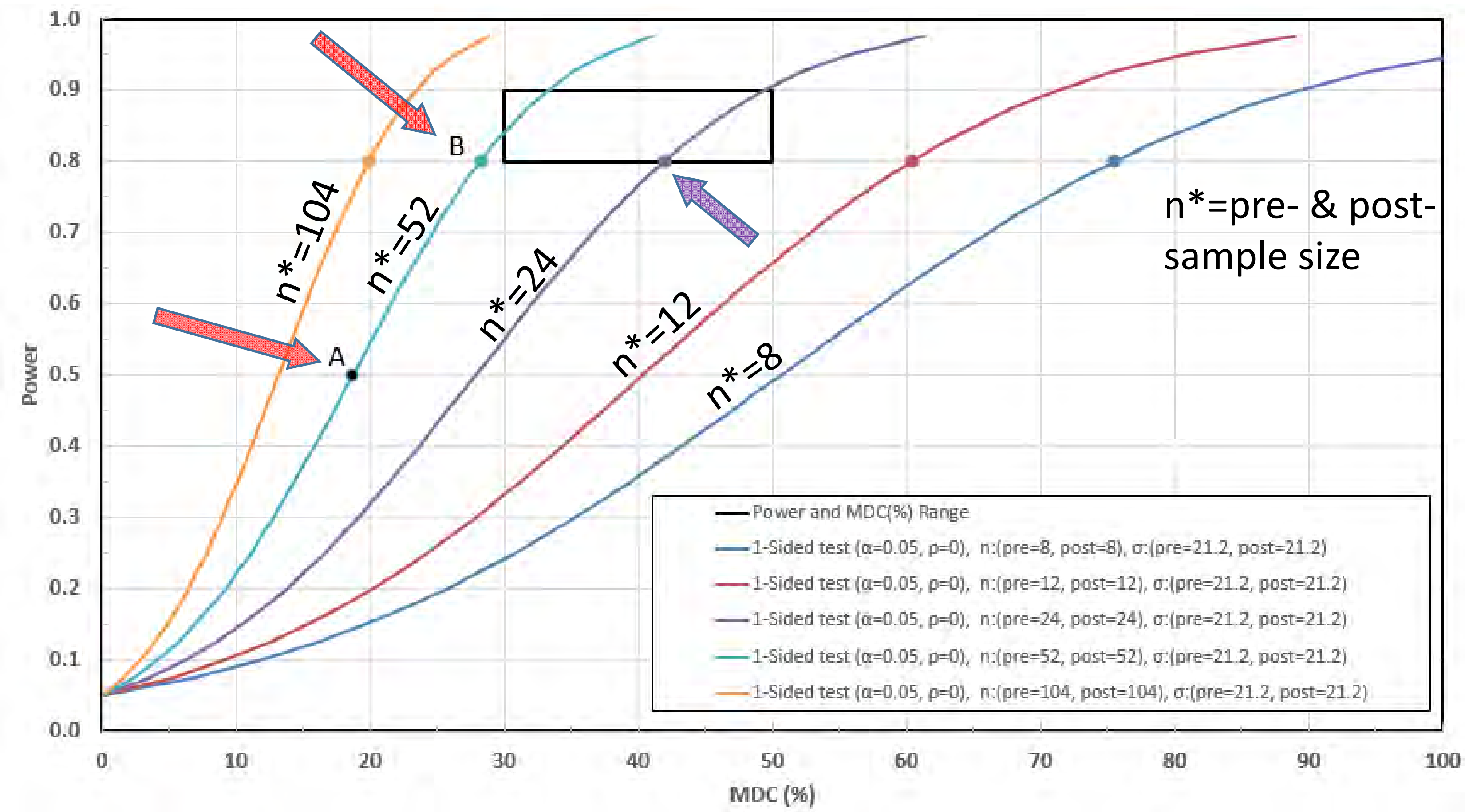
Power Curve for Alternative Sample Sizes



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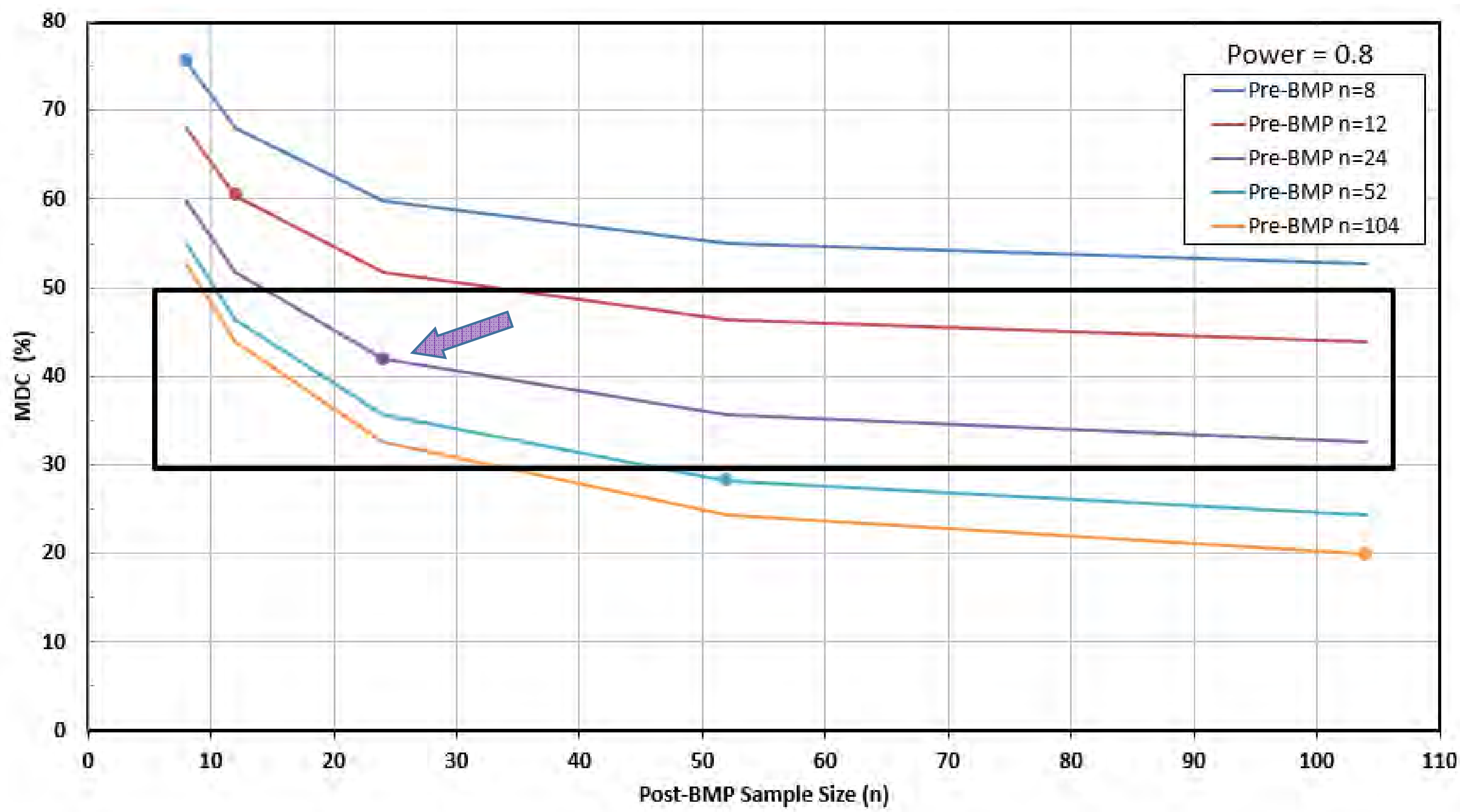
Alternative Post-BMP Samples for Power = 0.80



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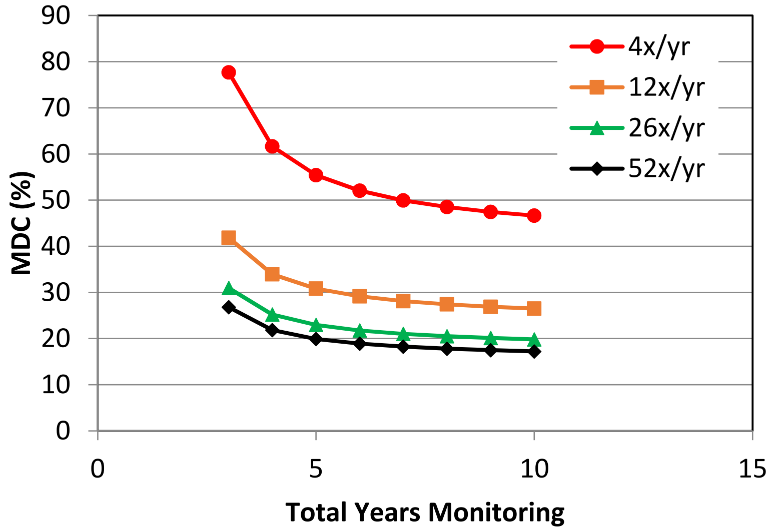
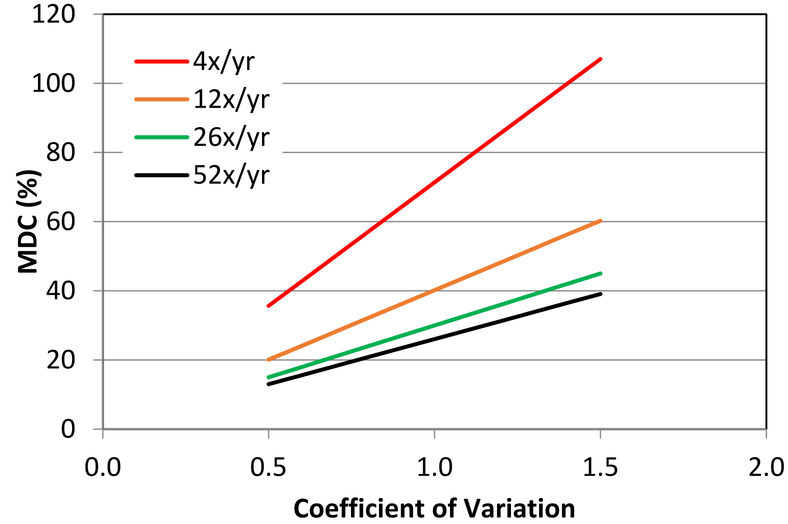
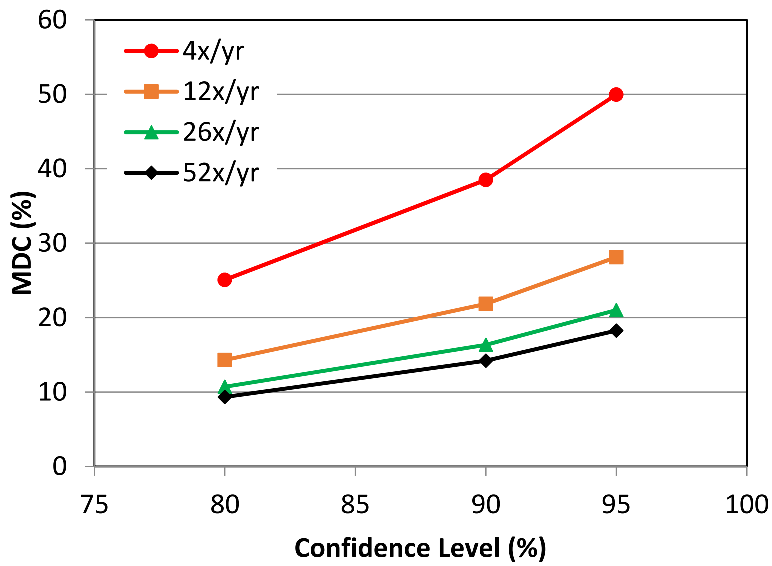
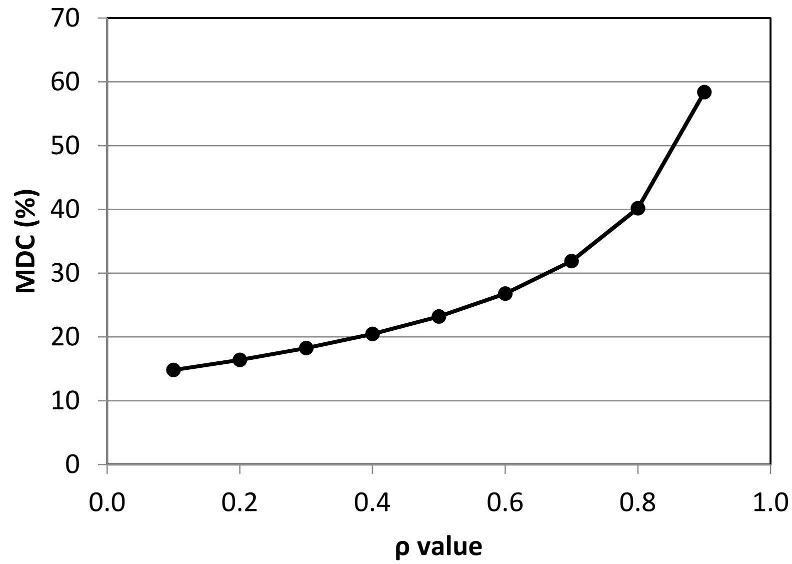
Alternative views









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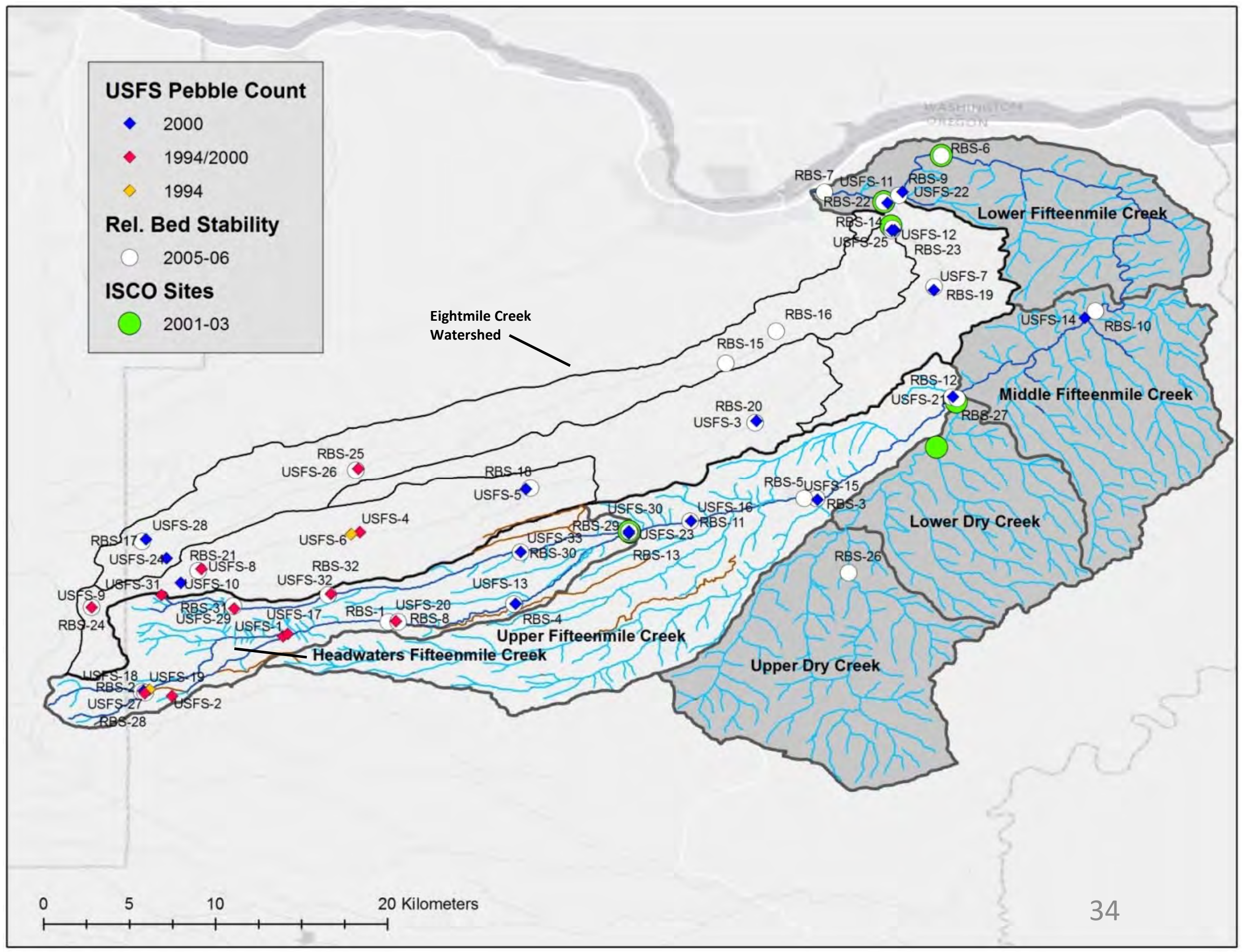
Example 3—Fifteenmile Cr. (OR) Repeated Observations

Existing data

- USFS pebble counts—1994 and 2000
- Relative bed stability (RBS) scores—2005-06
- Turbidity and TSS data using ISCO samplers—2000-03



Example 3—Fifteenmile Cr. (OR) Repeated Observations

Pebble count data used to calculate

- Percent fines (%<0.06mm, FN)
- Percent sand and fines (%<2mm, SAFN)
- $\log_{10}$ relative bed stability (LRBS)—ratio of the D_{50} to the critical diameter at bankfull flow

Justification for Using SAFN

- Easily and consistently measured over time using a standard pebble count
- Not sensitive to subjective interpretation and adjustments (in contrast to LRBS that depends on identification of bankfull width, which is then used with pool volume and woody debris to adjust the observed value)
- Existence of historical and reference data
- Addressed by the BMP
- Important to a wide variety of aquatic life

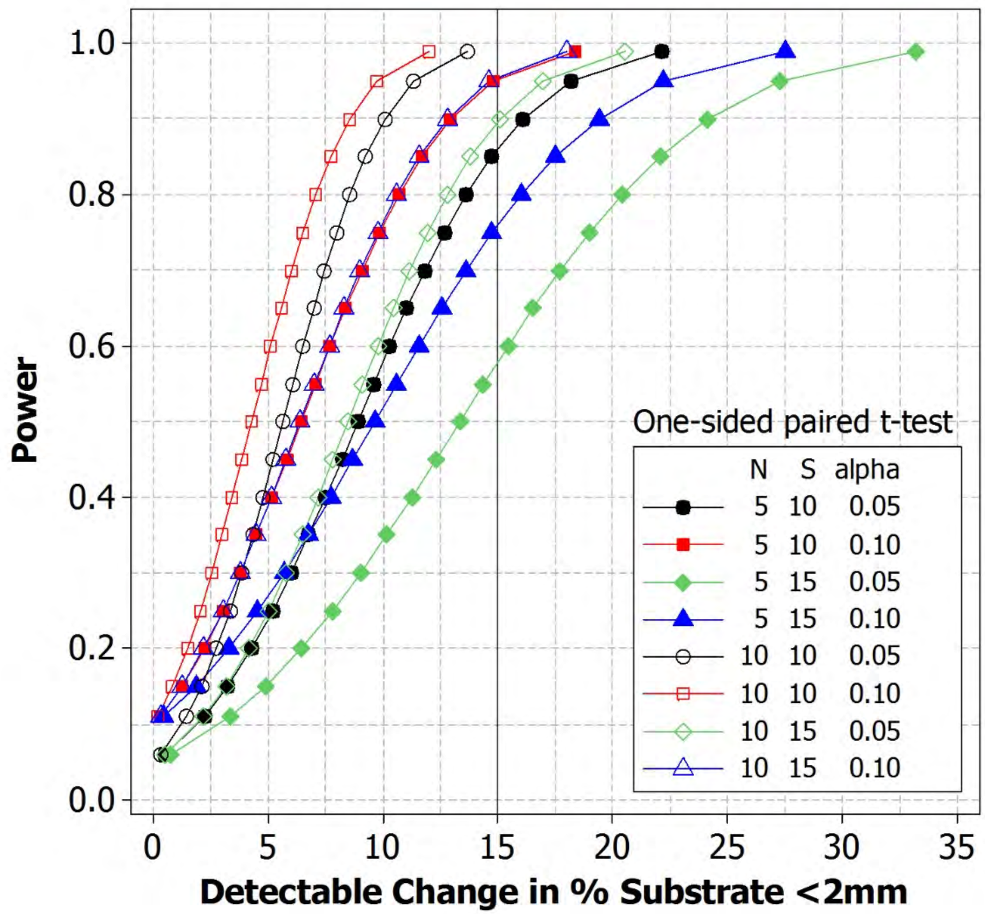
Example 3—Fifteenmile Cr. (OR) Repeated Observations

Range of SAFN variability, i.e., (s)
- 10% to 15%

Likely sample sizes
- 5 to 10

Confidence level
- 90% and 95%

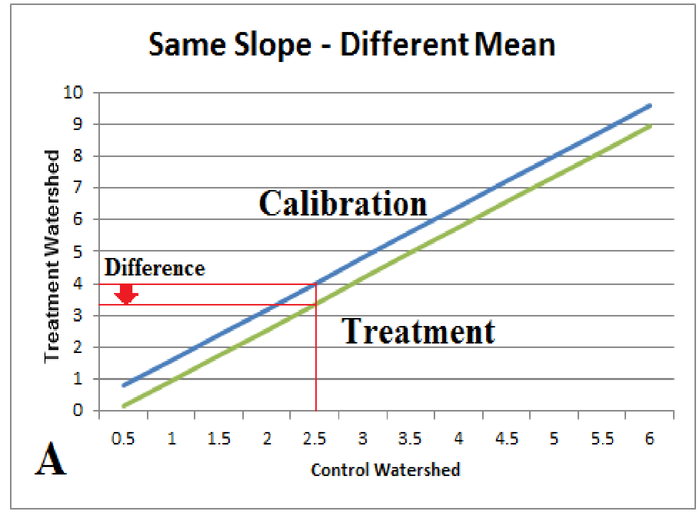
Meaningful change
- 5% loss in biological resource correlates to 15% increase in SAFN

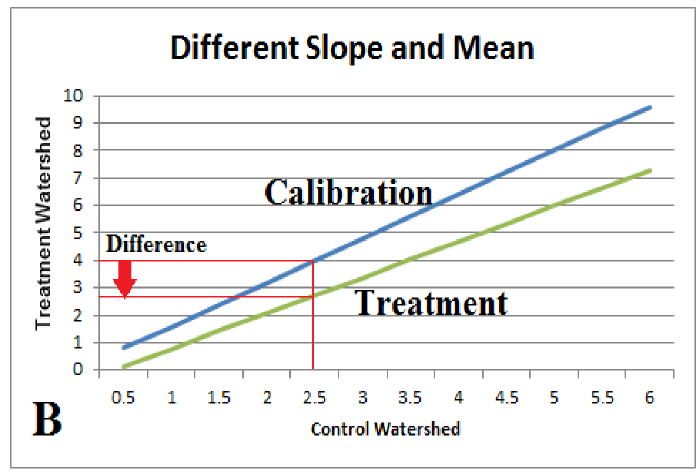


Paired Watershed Design

- Analysis of Covariance (ANCOVA)
  1. Obtain paired data
  2. Select appropriate form of model
  3. Calculate adjusted means and confidence intervals
- Same slope:

  $Y_t = \beta_0 + \beta_1(\text{Period}) + \beta_2 X_t + e_t$
  - H_O: $\beta_1 = 0$
  - H_a: $\beta_1 < 0$

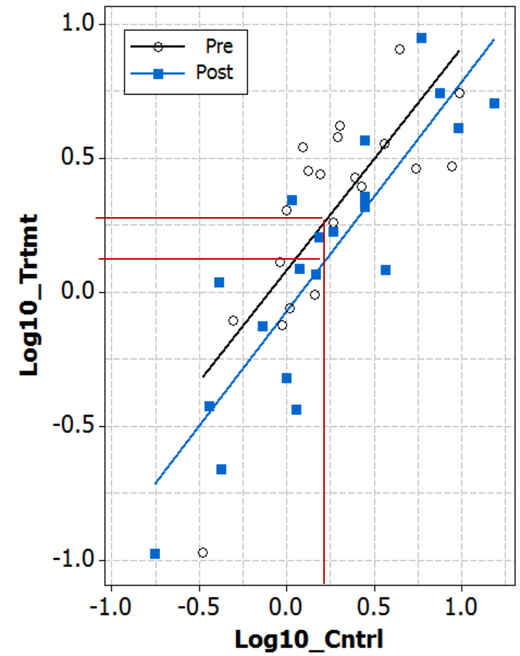




Paired Watershed Design

- **Analysis of Covariance (ANCOVA)**

Source	DF	Seq SS	Adj SS	Adj MS	F	P	
Log10_Cntrl	1	5.5861	5.4614	5.4614	81.94	0.000	
Period	1	0.2083	0.2083	0.2083	3.13	**0.085**	← !!!
Error	37	2.4661	2.4661	**0.0667** ← MEAN SQUARED ERROR			
Total	39	8.2605					

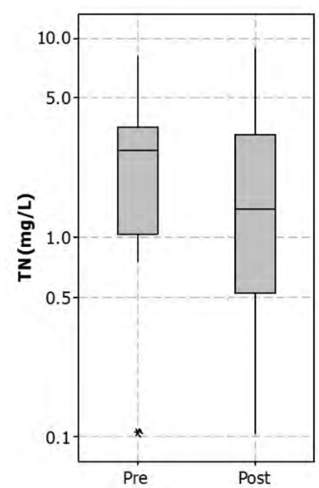


Recall Slide 25 for one-way ANOVA results:

One-way ANOVA: Log10_Trtmt versus Period

Source	DF	SS	MS	F	P	
Period	1	0.333	0.333	1.60	**0.214**	← NOT STATISTICALLY DIFFERENT
Error	38	7.928	**0.209** ← MEAN SQUARED ERROR			
Total	39	8.261				

S = 0.4567   R-Sq = 4.03%   R-Sq(adj) = 1.51%



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Paired Watershed Design

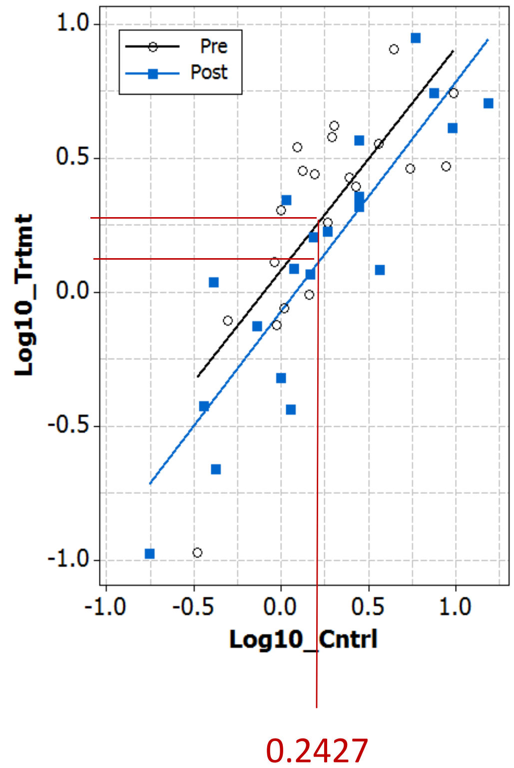
- **Analysis of Covariance (ANCOVA)**

Term	Coef	SE Coef	T	P
Constant	0.00429	0.04670	0.09	0.927
Log10_Cntrl	0.84618	0.09348	9.05	0.000
Period:Pre	0.07226	0.04087	1.77	0.085

Period

Pre: Log10_Trtmt = 0.0765538 + 0.846185 Log10_Cntrl

Post: Log10_Trtmt = -0.0679728 + 0.846185 Log10_Cntrl



- **Compute difference in regression equations at LS Mean for covariate**

Pre: 0.0765538 + 0.846185 (0.2427) → **0.2829**

Post: -0.0679728 + 0.846185 (0.2427) → **0.1374**

$$\text{Change}(\%) = 100 \times \left[1 - \frac{10^{0.1374}}{10^{0.2829}}\right] = 28\%$$

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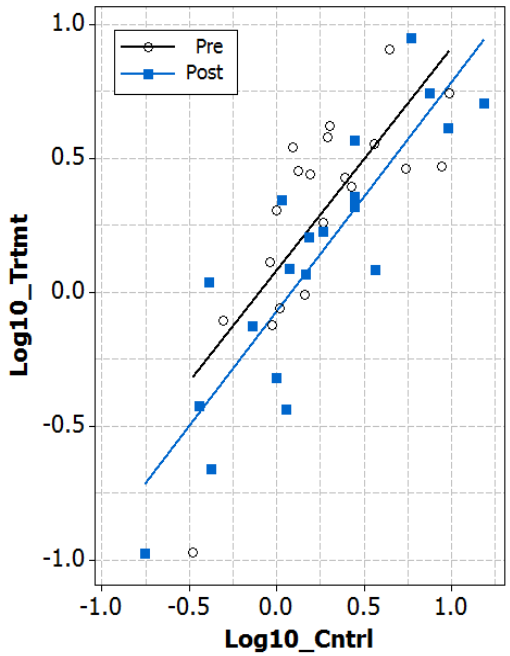
Paired Watershed Design

$$\mathrm{MDC} = t_{(n_{pre}+n_{post}-3)} \times s_{(\mathrm{lsmean}_{pre}-\mathrm{lsmean}_{post})}$$

$$s_{(\mathrm{lsmean}_{pre}-\mathrm{lsmean}_{post})} = \sqrt{\mathrm{MSE} \times \frac{2}{n} \times \mathrm{Factor}}$$



- $n_{pre} = n_{post}$ =20, df= 37, Power = 0.50
- 95% one-sided test, α=0.05, t = 1.687

$$\mathrm{MDC} = 1.687 \times \sqrt{0.0667 \times \frac{2}{20} \times 1} = 0.1378$$

$$\mathrm{MDC}(\%) = 100 \times [1 - 10^{-0.1378}] = \underline{27\%}$$

- 90% one-sided test, α=0.10, t = 1.305

$$\mathrm{MDC} = 1.305 \times \sqrt{0.0667 \times \frac{2}{20} \times 1} = 0.1066$$

$$\mathrm{MDC}(\%) = 100 \times [1 - 10^{-0.1066}] = \underline{22\%}$$

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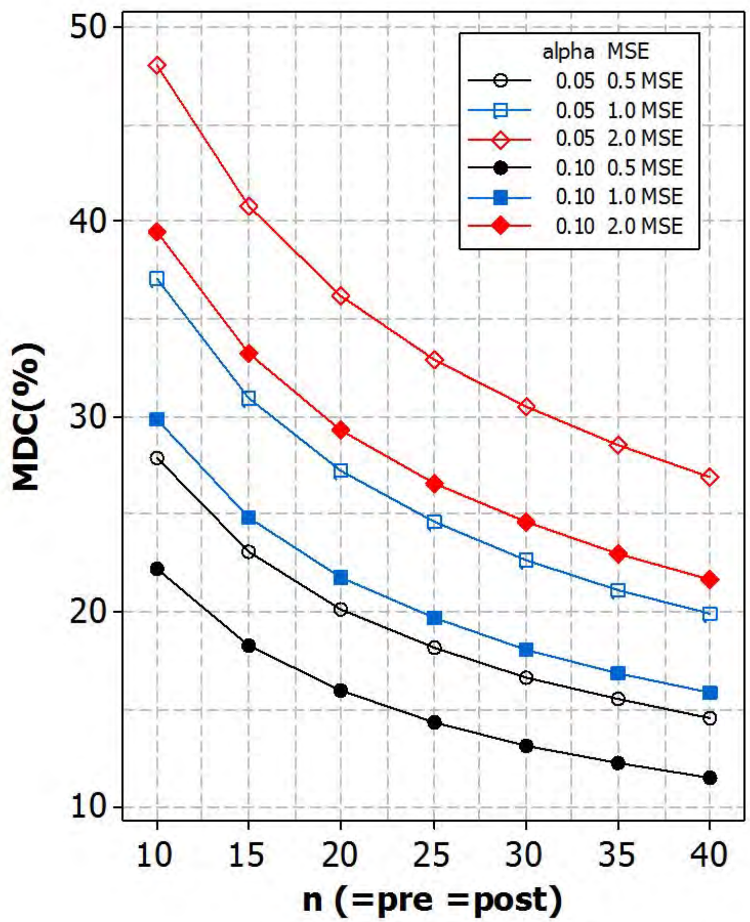
Paired Watershed Design

- MDC(%) for a variety of sample sizes and MSE
  - Power = 0.5
  - α = 0.05, 0.10 (one-sided test)
- Adjustments
  - Use pre-BMP calibration regression MSE



Summary

- Basic monitoring design options for evaluating BMP performance
- Sampling frequency issues
- Used summary statistic estimation to introduce trade-offs between sample size and confidence levels
- Trend detection
  - Power curves
  - Step trends (2-sample tests)
  - Paired tests ("repeated observation")
  - Paired watershed

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Resources (Computer code)

- R
    - Package: stats
        - help.search("power", package="stats")
            - Balanced One-Way Analysis of Variance Tests
            - Two-Sample Test for Proportions
            - One and two sample t tests
    - Package: pwr
        - Similar to above
        - Unequal sample size
- Commercial Software
    - Minitab, SAS, Matlab, and others

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R Code Example

power.t.test

- Pre- & Post- sample size is constant
- Specify s

pwr.t2n.test

- Different sample sizes
- s = 1

```r
library("pwr")

sig.level_in  <- 0.05
power_in      <- 0.8
pre_mean      <- 4
sd_in         <- 1
n_in          <- 52

x<-power.t.test(n = n_in, delta = NULL, sd = sd_in, sig.level = sig.level_in ,
        power = power_in, type = "two.sample" , alternative = "one.sided",
        strict = TRUE)
x
100*(x$delta/pre_mean)

y<-pwr.t2n.test(n1 = n_in, n2= n_in, d = NULL, sig.level = sig.level_in,
        power = power_in, alternative = "greater")
y
100*(y$d/pre_mean)
```

```
     Two-sample t test power calculation

              n = 52
          delta = 0.4909048
             sd = 1
      sig.level = 0.05
          power = 0.8
    alternative = one.sided

NOTE: n is number in *each* group

> 100*(x$delta/pre_mean)
[1] 12.53896
```

```
     t test power calculation

             n1 = 52
             n2 = 52
              d = 0.4909072
      sig.level = 0.05
          power = 0.8
    alternative = greater

> 100*(y$d/pre_mean)
[1] 12.27268
```

R Code for Example 1

2-sample, 1-sided t test Normal Distribution

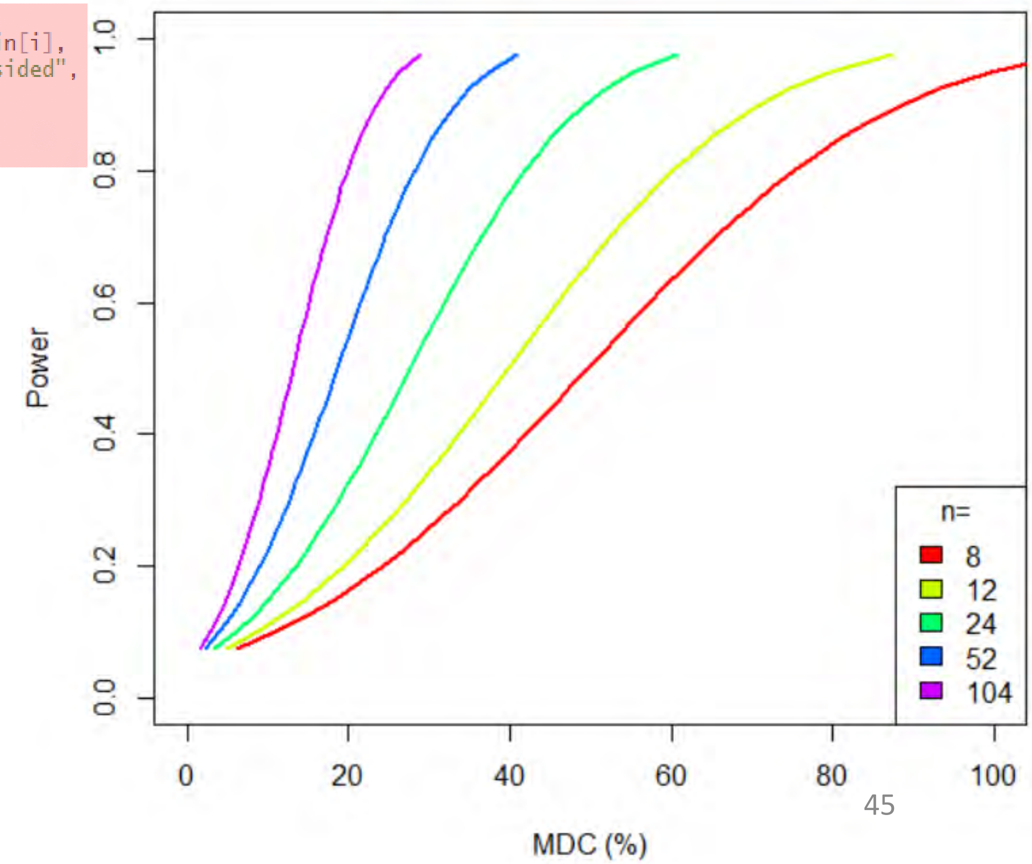
```r
sig.level_in   <- 0.05
power_in       <- seq(sig.level_in+.025 , 0.975, by=0.025)
pre_mean       <- 36.9
sd_in          <- 21.2
n_in           <- c(8, 12, 24, 52, 104)
power_len      <- length(power_in)
n_len          <- length(n_in)

MDC <- array(numeric(power_len*n_len), dim=c(power_len,n_len))

for (j in 1:n_len) {
  for (i in 1:power_len) {
      x<-power.t.test(n = n_in[j], delta = NULL, sd = sd_in,
                      sig.level = sig.level_in , power = power_in[i],
                      type = "two.sample" , alternative = "one.sided",
                      strict = TRUE)

      MDC[i,j] <- 100*(x$delta/pre_mean)
  }
}

# # set up graph
 yrange <- round(range(power_in))
 xrange <- c(0, 100)
 colors <- rainbow(n_len)
 plot(xrange, yrange, type="n",
      xlab="MDC (%)",
      ylab="Power" )
#
# # add power curves
 for (j in 1:n_len){
   lines(MDC[,j], power_in, type="l", lwd=2, col=colors[j])
 }
#
# # add legend
 legend("bottomright", title="n= ", as.character(n_in),
        fill=colors)
```



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