

Power Analysis for National Park Service Lake Chemistry Data from 2008 to 2011

Sierra Nevada Network

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INTRODUCTION

The Sierra Nevada Network (SIEN) of the National Park Service identified lake chemistry as one of its Vital Signs for long-term monitoring. Since 2008, chemistry metrics at 24 or 25 SIEN lakes have been monitored each year to provide data for status and trend estimation. Status estimation occurs annually, and trend estimation will occur every five years. The goal of this current work is to analyze the data from the surveys conducted in 2008 through 2011, identify covariates that would improve trend estimation and variance components estimation, and update the analysis of the power to detect trend.

SAMPLING DESIGN

The SIEN lakes monitored each year were selected with a generalized random tessellation stratified (GRTS) design (Stevens and Olsen 2003). The sample was selected with unequal probability sampling based on classes formed from a cost-surface model of travel time to SIEN locations. The revisit design is described as [(1-0), (1-3)] design in the notation of McDonald (2003), in which a single panel of 7 or 8 sites is visited annually and 4 panels of 17 sites are visited on an alternating basis then rested for the next three consecutive years.

DATA ANALYSIS

Model selection

Model selection is conducted using the observed data without accounting for data missing due to detection limits. Therefore, measurements falling below detection levels that are not flagged by the lab as minimum detection limit (MDL) data are used as the best available measurements. While trend and status estimation employ imputation techniques to account for MDL data, model selection and variance components estimation must be conducted with the data at-hand.

The trend model proposed by Piepho and Ogutu (2002) is used to assess trend and the corresponding power analysis. Initial model covariates describing basin characteristics (Table 1) are identified with plots and assessments of linear correlation. Simple linear regression models are applied to logarithmically-transformed outcomes of interest so that multiplicative trend may be assessed. The logarithmic transformation also assists in meeting regression assumptions on residuals. Stepwise regression with AIC as the model selection criterion is used on the simple linear regression model, then the random effects are added with the *lmer* function in the lme4 package for linear mixed modeling in R (2013). AIC is used to determine if other fixed effects could be removed after adding the random effects, and all fixed effects with t-statistics greater than 2.00 are retained. The time covariate is always included in the model regardless of its statistical significance. The covariates in the final models are provided in Table 2 and the variance components estimates are given in Table 3.

Table 1: Description of potential modeling covariates

Field name	Description
W_perimeter	Watershed perimeter length (m)
WA	Watershed area (m2)
Z_Min	Elevation - minimum
Z_Max	Elevation - maximum
Z_Mean	Elevation - mean
WA_3D	Watershed area (m2) - calculated using 3D surface
Max_Slope	Maximum slope (%)
Mean_Slope	Mean slope (%)
asp_0	Percent basin area with aspect between 0 - 45 degrees
asp_45	Percent basin area with aspect between 45 - 90 degrees
asp_90	Percent basin area with aspect between 90 - 135 degrees
asp_135	Percent basin area with aspect between 135 - 180 degrees
asp_180	Percent basin area with aspect between 180 - 225 degrees
asp_225	Percent basin area with aspect between 225 - 270 degrees
asp_270	Percent basin area with aspect between 270 - 315 degrees
asp_315	Percent basin area with aspect between 315 - 360 degrees
Nslp	Percent basin area with greater than 30% slope and north facing (315-45 degrees)
barren	Percent basin area that is non-vegetated
water	Percent basin area covered with water
shore_line	Lake shore line length (m)
lake_area	Lake area (ha)
WA_LA	Ratio of watershed area to lake area
P_LA	Ratio of shoreline length to lake area
allv	Percent basin with alluvium bedrock type
calc	Percent basin with calcareous-meta-sed (limestone, calcareous sandstone, marble) bedrock type
fel	Percent basin with felsic bedrock type
FI	Percent basin with felsic intrusive bedrock type
FV	Percent basin with felsic volcanic bedrock type
ice	Percent basin with permanent ice cover
II	Percent basin with intermediate intrusive bedrock type
IM	Percent basin with intermediate metamorphic bedrock type
MI	Percent basin with mafic intrusive bedrock type
MM	Percent basin with mafic metamorphic bedrock type
neo	Percent basin with neoglacial till/talus/colluvium bedrock type
PT	Percent basin with Pleistocene till bedrock type

Table 2: Covariates in final trend model*

Analyte	Covariates
ANC	Z_Max, Z_Mean
Ca	Max_Slope, X0, X45, X90, X135, X180, X225, X270, X315, Barren
Cl	Park, X45, Nslp, WYear:Park
DIN:TP	WYear ² , Mean_Slope, Barren
K	FI
Mg	X45, Nslp, FI
Na	Mean_Slope, X45, Nslp, Barren
NO ₃	Mean_Slope, Barren
PC	Park, WA, WA_3D
pH	Max_Slope, X45
PN	Park, Z_Max, Z_Mean, Barren
PN:PP	WYear ² , Park, Barren
PP	WYear ² , WYear ³ , Min_Slope
SO ₄	Z_Max
Spec. Cond.	WA, Max_Slope, X45, lake_area, WA_LA
TDN	Park, Z_Mean, Min_Slope, FI
TDP	Nslp

* All models contain a fixed effect for Year

Table 3: Estimated variance components

Analyte	$\hat{\sigma}_b^2$	$\hat{\sigma}_a^2$	$\hat{\sigma}_t^2$	$\hat{\sigma}_c^2$
ANC	0.0000	0.1700	0.0026	0.1610
Ca	0.0692	0.1507	0.0128	0.3540
Cl	0.0000	0.2781	0.0560	0.1134
DIN:TP	0.6869	1.5733	0.5778	3.7014
K	0.0000	0.0387	0.0040	0.2691
Mg	0.0587	0.4009	0.0014	0.0097
Na	0.0019	0.2070	0.0004	0.0064
NO ₃	0.0000	1.5493	0.0258	0.3463
PC	0.0063	0.2071	0.0302	0.0602
pH	0.0000045	0.000068	0.000049	0.001354
PN	0.0000	0.7128	0.0468	0.1736
PN:PP	0.3007	0.9271	0.1652	0.1057
PP	0.0176	0.0119	0.0338	0.1569
SO ₄	0.0559	0.6437	0.0809	0.5776
Spec. Cond.	0.0000	0.2059	0.0029	0.0851
TDN	0.0068	0.0406	0.0082	0.1830
TDP	0.0570	0.0000	0.0285	0.5407

Note that year-to-year variation is estimated as 0 for several outcomes of interest. Annual random variation of 0 is unlikely; year-to-year variation may not be estimable with only four years of data for these outcomes. Power analysis for these indicators may underestimate the power to detect trend since even small levels of year-to-year variation can greatly impact the power to detect trend. Therefore, power to detect trends in metrics with estimates of 0 year-to-year variation should be considered low and interpreted with caution.

Model results are provided in Appendix A. Model selection was straightforward for most outcomes. The DIN:TP ratio exhibited numerous zeros, so a trend model that accounts for excess zeros (hurdle model or zero-inflated model) may be preferred to a linear mixed model in future trend analysis rather than the current analysis for model selection and variance component estimation. A location shift of 0.01 was used to accommodate the logarithmic transformation. Outliers were observed in several outcomes, and their validity was confirmed with Andi Heard. Most analyses conducted with and without the outliers indicated that their presence did not impact inference. However, a single outlier in the PN data set with value 0.2734 was removed to improve the fit and reduce the influence of that data point on the variance components estimates. Residual diagnostic

plots for the PP outcome indicated some linear patterns that may suggest some non-randomness in the data set.

Power analysis

The power analysis is conducted with Monte Carlo power simulation for the trend test described by Piepho and Ogutu (2002). The four years of SIEN lake chemistry monitoring data are used to obtain estimates of the baseline population mean and the variance components. These estimates provide the basis for simulating populations exhibiting known trends over a 30-year period. Two levels of annual trend (1% and 4%) are considered. Since two-sided trend tests are of interest, trend could occur in either direction. Trend tests of increases in the population mean exhibit slightly lower power to detect trend than population declines (Gerrodette 1993), so power analysis simulations are conducted for annual increases of 1% and 4% in the population mean. Simulations consist of 500 iterations, and power is calculated as the proportion of the 500 iterations for which the null hypothesis is rejected in favor of the alternative hypothesis of trend.

The corresponding net trend is provided in Table 4 as a function of time. For example, a 1% annual decline in a metric over time will result in a 5% decrease in the mean after 5 years (0.95) and a 26% decline in the mean after 30 years (0.74). Similarly, a 1% annual increase in the population mean results in a 5% net increase after 5 years and a 35% increase after 30 years.

Table 4: Net trend for values of annual trend over time

Years	-1% annual trend	-4% annual trend	1% annual trend	4% annual trend
5	0.95	0.82	1.05	1.22
10	0.90	0.66	1.10	1.48
15	0.86	0.54	1.16	1.80
20	0.82	0.44	1.22	2.19
25	0.78	0.36	1.28	2.67
30	0.74	0.29	1.35	3.24

The results of the power analysis are provided in Figures 1 through 17 and in Table 5. Note that the year-to-year variation is assumed to be zero for ANC, Cl, K, NO₃, PN, and Specific Conductance. Power for these outcomes should be considered at best a lower bound.

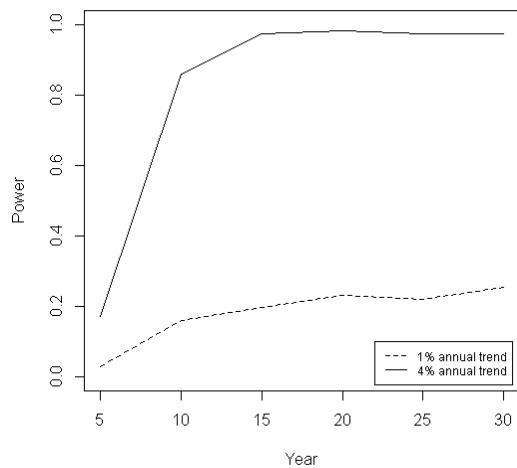


Figure 1. Power to detect two values of annual trend in **ANC** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

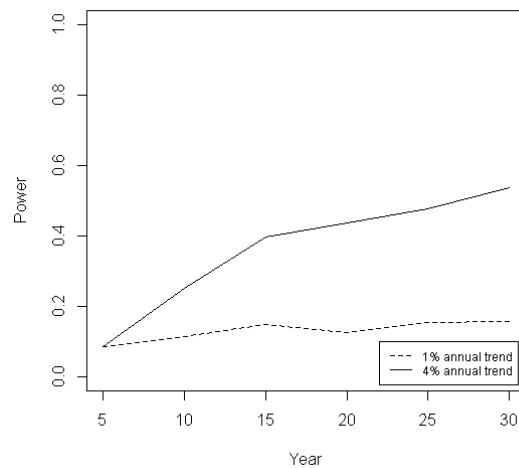


Figure 2. Power to detect two values of annual trend in **Ca** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

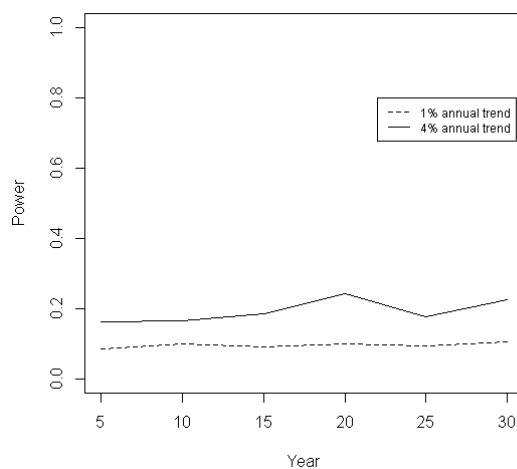


Figure 3. Power to detect two values of annual trend in **CI** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

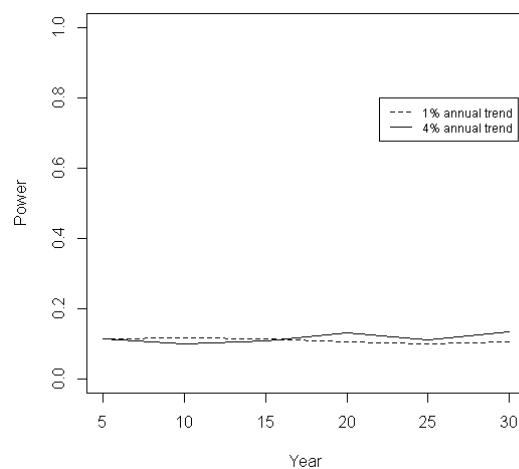


Figure 4. Power to detect two values of annual trend in **DIN:TP** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

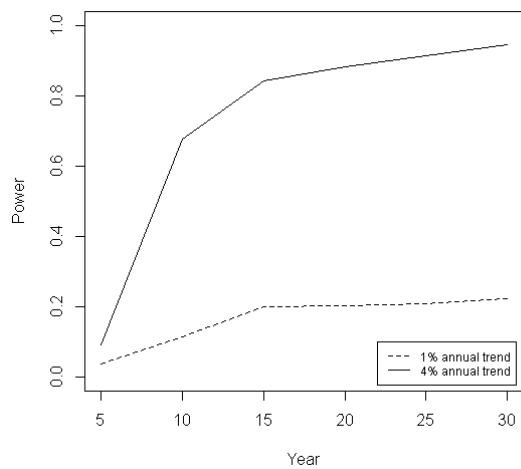


Figure 5. Power to detect two values of annual trend in **K** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

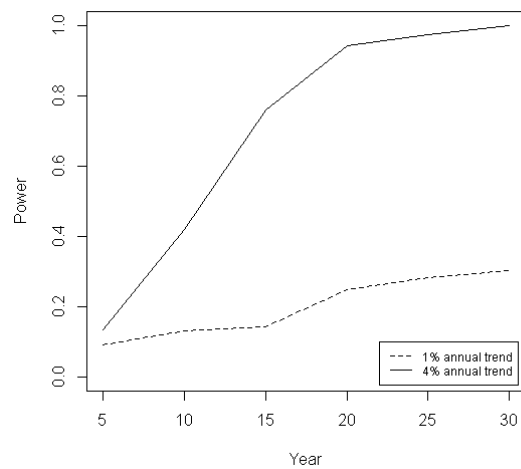


Figure 6. Power to detect two values of annual trend in **Mg** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

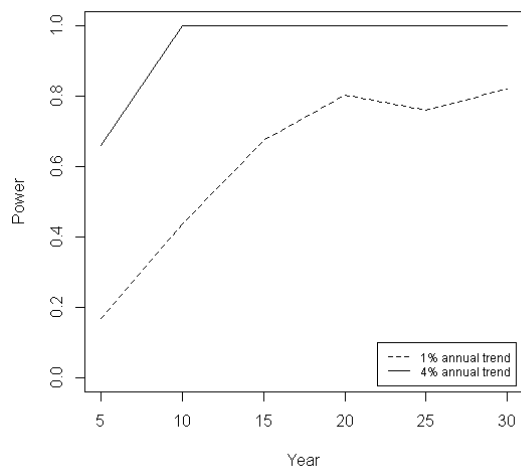


Figure 7. Power to detect two values of annual trend in **Na** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

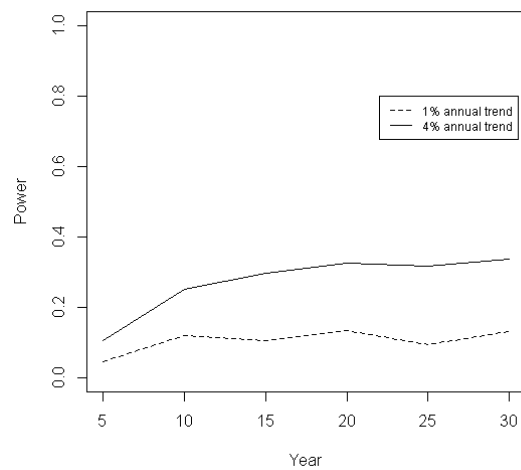


Figure 8. Power to detect two values of annual trend in **NO₃** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

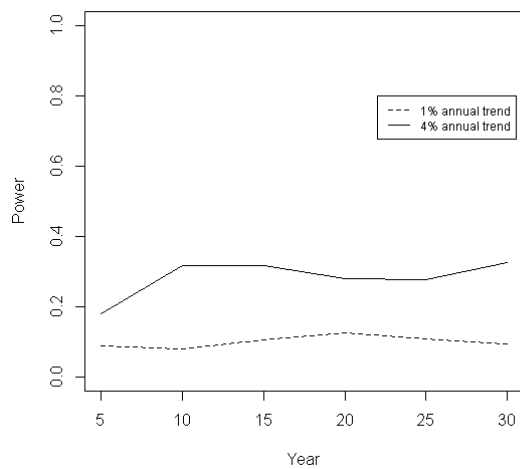


Figure 9. Power to detect two values of annual trend in **PC** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

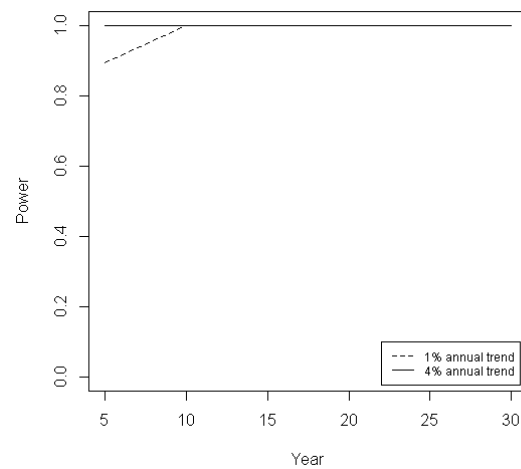


Figure 10. Power to detect two values of annual trend in **pH** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

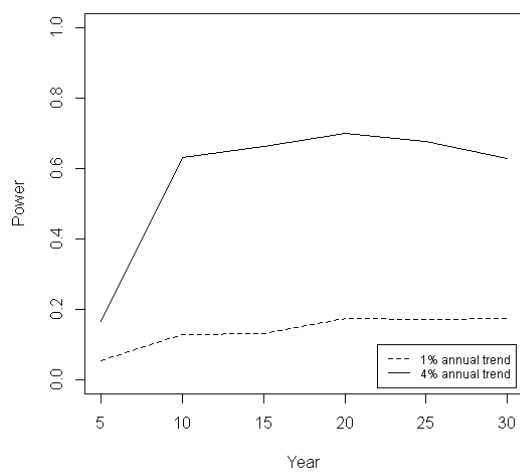


Figure 11. Power to detect two values of annual trend in **PN** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

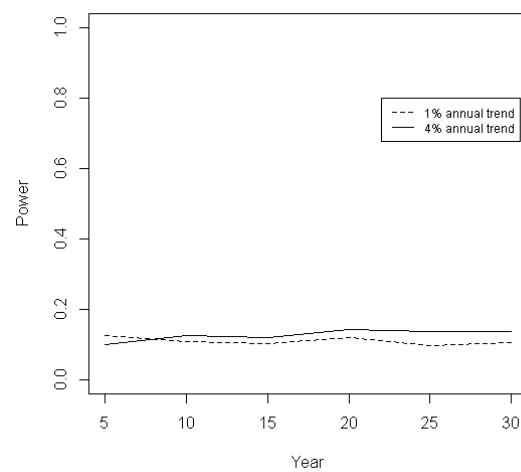


Figure 12. Power to detect two values of annual trend in **PN:PP** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

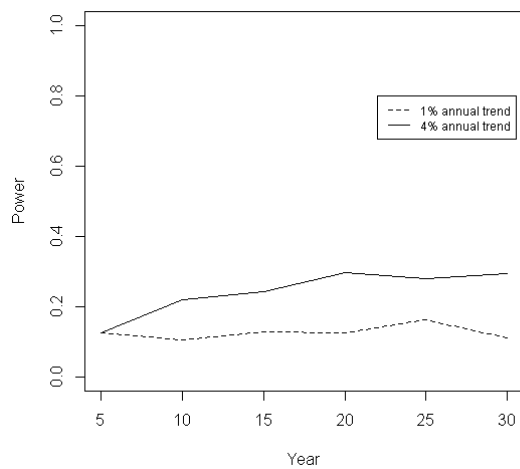


Figure 13. Power to detect two values of annual trend in **PP** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

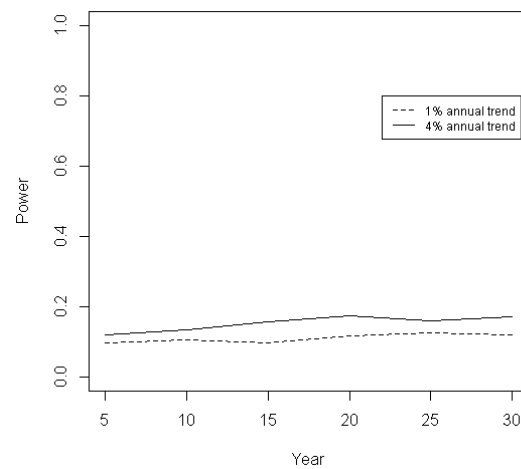


Figure 14. Power to detect two values of annual trend in **SO₄** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

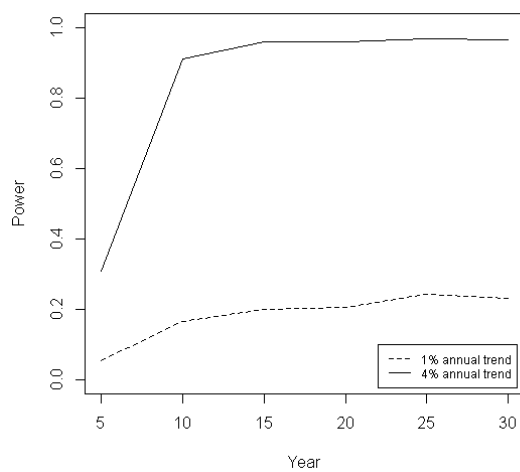


Figure 15. Power to detect two values of annual trend in **Specific Conductance** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

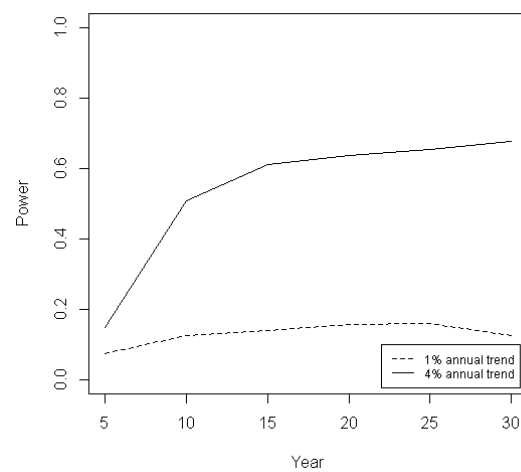


Figure 16. Power to detect two values of annual trend in **TDN** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

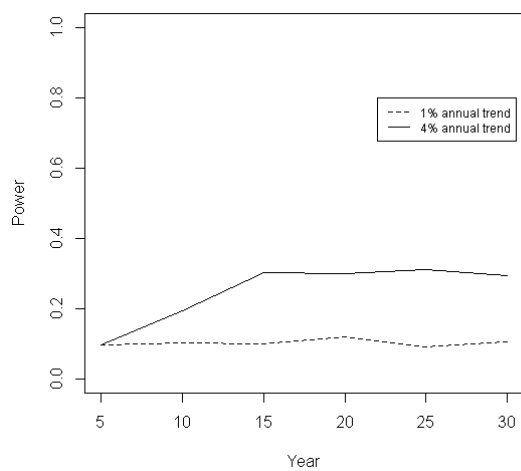


Figure 17. Power to detect two values of annual trend in **TDP** for annual surveys of 25 lakes with a [(1-0),(1-3)] revisit design.

Table 5: Power by years in monitoring program and outcome of interest.

Outcome	Trend	5 years	10 years	15 years	20 year	25 years	30 years
ANC	0.01	0.03	0.16	0.20	0.23	0.22	0.25
ANC	0.04	0.17	0.86	0.98	0.98	0.98	0.98
Ca	0.01	0.08	0.11	0.15	0.12	0.15	0.16
Ca	0.04	0.08	0.25	0.40	0.44	0.48	0.54
Cl	0.01	0.08	0.10	0.09	0.10	0.09	0.11
Cl	0.04	0.16	0.17	0.18	0.24	0.18	0.22
DIN:TP	0.01	0.11	0.12	0.11	0.11	0.10	0.11
DIN:TP	0.04	0.11	0.10	0.11	0.13	0.11	0.13
K	0.01	0.04	0.11	0.20	0.20	0.21	0.22
K	0.04	0.09	0.68	0.84	0.88	0.91	0.95
Mg	0.01	0.09	0.13	0.14	0.25	0.28	0.30
Mg	0.04	0.13	0.42	0.76	0.94	0.97	1.00
Na	0.01	0.17	0.44	0.67	0.80	0.76	0.82
Na	0.04	0.66	1.00	1.00	1.00	1.00	1.00
Nitrate	0.01	0.05	0.12	0.11	0.13	0.09	0.13
Nitrate	0.04	0.10	0.25	0.30	0.32	0.32	0.34
PC	0.01	0.09	0.08	0.11	0.13	0.11	0.09
PC	0.04	0.18	0.32	0.32	0.28	0.28	0.32
pH	0.01	0.89	1.00	1.00	1.00	1.00	1.00
pH	0.04	1.00	1.00	1.00	1.00	1.00	1.00
PN	0.01	0.05	0.13	0.13	0.17	0.17	0.17
PN	0.04	0.16	0.63	0.66	0.70	0.68	0.63
PN:PP	0.01	0.13	0.11	0.10	0.12	0.10	0.11
PN:PP	0.04	0.10	0.12	0.12	0.14	0.14	0.14
PP	0.01	0.13	0.11	0.13	0.13	0.16	0.11
PP	0.04	0.12	0.22	0.24	0.30	0.28	0.29
Sulfate	0.01	0.10	0.11	0.10	0.12	0.12	0.12
Sulfate	0.04	0.12	0.13	0.16	0.17	0.16	0.17
Sp Cond	0.01	0.05	0.17	0.20	0.21	0.24	0.23
Sp Cond	0.04	0.31	0.91	0.96	0.96	0.97	0.97
TDN	0.01	0.07	0.12	0.14	0.16	0.16	0.13
TDN	0.04	0.15	0.51	0.61	0.64	0.65	0.68
TDP	0.01	0.10	0.10	0.10	0.12	0.09	0.11
TDP	0.04	0.10	0.19	0.30	0.30	0.31	0.29

DISCUSSION AND CONCLUSIONS

For outcomes with non-zero estimates of year-to-year variation, the highest power to detect trend is found for Mg, Na, and pH. Despite the relatively-high year-to-year variation observed in the Mg measurements, the random-slope variation and residual variation are very small for this outcome and acceptable power to detect large trend (4% annually) is attained. The lowest power is observed in indicators with high random-slope variation or variance components with a large magnitude.

Even with the assumption of no year-to-year variation for the nitrate trends, the power to detect trends in nitrates is very low due to the large magnitude of the other measurable variance components. Previous work with Sierra Nevada lakes pilot data indicates that nitrates exhibit considerable year-to-year variation as well.

Additional years of monitoring will improve the ability to obtain estimates of year-to-year variance for all outcomes of interest. In several cases, the variance components obtained in this exercise are quite similar to those obtained from pilot data sets for the 2008 power analysis. However, for most outcomes, the random slope variance is estimated to be much larger than the pilot data indicated. The new estimates of random-slope variation are often an order of magnitude larger than the previous estimates and impact the power to detect population-level trends. The estimates of the variation of site-level slopes may improve with time and more accurate estimation of long-term trend within a site. However, the larger variation may simply indicate a more heterogeneous sample than was used for the previous power analysis.

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APPENDIX A: Results of covariate selection in the trend model

ANC

Linear mixed model fit by REML

Formula: $\log(\text{ANC}) \sim \text{WYear} + \text{Z_Max} + \text{Z_Mean} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: ANC

AIC BIC logLik deviance REMLdev

210.2 233.2 -96.08 155.3 192.2

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.1700025	0.412314	
	WYear	0.0025886	0.050878	-0.054
Year	(Intercept)	0.0000000	0.000000	
Residual		0.1609542	0.401191	

Number of obs: 96, groups: site_id, 75; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	3.5196789	0.5208761	6.757
WYear	-0.0840658	0.0477444	-1.761
Z_Max	0.0016424	0.0005474	3.000
Z_Mean	-0.0016468	0.0006114	-2.694

Ca

Linear mixed model fit by REML

Formula: $\log(\text{Ca}) \sim \text{WYear} + \text{Max_Slope} + \text{X0} + \text{X45} + \text{X90} + \text{X135} + \text{X180} + \text{X225} + \text{X270} + \text{X315} + \text{Barren} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.150729	0.38824	
	WYear	0.012797	0.11312	-0.917
Year	(Intercept)	0.069153	0.26297	
Residual		0.354021	0.59500	

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	52.1697204	12.1731008	4.286
WYear	0.0734042	0.1332124	0.551
Max_Slope	0.0007116	0.0003172	2.244
X0	-0.5000431	0.1226854	-4.076
X45	-0.5161356	0.1236762	-4.173
X90	-0.5015263	0.1211104	-4.141
X135	-0.4970427	0.1219386	-4.076
X180	-0.4700967	0.1223525	-3.842
X225	-0.5042654	0.1226972	-4.110
X270	-0.4862785	0.1214425	-4.004
X315	-0.5159638	0.1235350	-4.177
Barren	0.0067812	0.0029093	2.331

Cl

Linear mixed model fit by REML

Formula: $\log(\text{Cl}) \sim \text{WYear} + \text{Park} + \text{X45} + \text{Nslp} + \text{WYear}:\text{Park} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: Cl

	AIC	BIC	logLik	deviance	REMLdev
	158.7	186.9	-68.36	103.4	136.7

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.278079	0.52733	
	WYear	0.056049	0.23675	-1.000
Year	(Intercept)	0.000000	0.00000	
Residual		0.113444	0.33681	

Number of obs: 96, groups: site_id, 75; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	1.684222	0.143447	11.741
WYear	-0.321785	0.058862	-5.467
ParkY0SE	-0.465604	0.206903	-2.250
X45	-0.011214	0.004562	-2.458
Nslp	-0.014434	0.003529	-4.090
WYear:ParkY0SE	0.250462	0.096611	2.592

DIN_TP

Linear mixed model fit by REML

Formula: $\log(\text{DIN_TP} + 0.01) \sim \text{WYear} + \text{WYear}^2 + \text{Mean_Slope} + \text{Barren} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: DIN_TP

	AIC	BIC	logLik	deviance	REMLdev
	466.5	492.6	-223.3	432.4	446.5

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	1.57329	1.25431	
	WYear	0.57777	0.76011	-1.000
Year	(Intercept)	0.68686	0.82877	
Residual		3.70138	1.92390	

Number of obs: 100, groups: site_id, 75; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	-5.992237	1.072107	-5.589
WYear	3.309382	1.452249	2.279
WYear ²	-1.003355	0.462081	-2.171
Mean_Slope	0.029436	0.014042	2.096
Barren	0.036369	0.009699	3.750

K

Linear mixed model fit by REML

Formula: $\log(K) \sim WYear + FI + (1 | Year) + (1 + WYear | site_id)$

Data: K

AIC	BIC	logLik	deviance	REMLdev
186.8	207.2	-85.41	152.6	170.8

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.0387457	0.19684	
	WYear	0.0040462	0.06361	-0.527
Year	(Intercept)	0.0000000	0.00000	
Residual		0.2691357	0.51878	

Number of obs: 95, groups: site_id, 74; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	2.013412	0.210563	9.562
WYear	-0.111624	0.049798	-2.242
FI	-0.006111	0.002480	-2.464

Mg

Linear mixed model fit by REML

Formula: $\log(Mg) \sim WYear + X45 + Nslp + FI + (1 | Year) + (1 + WYear | site_id)$

Data: Mg

AIC	BIC	logLik	deviance	REMLdev
162.8	188.2	-71.4	111.3	142.8

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.4008835	0.633154	
	WYear	0.0013935	0.037330	-1.000
Year	(Intercept)	0.0586620	0.242202	
Residual		0.0097013	0.098495	

Number of obs: 94, groups: site_id, 74; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	1.785673	0.339857	5.254
WYear	0.155789	0.109777	1.419
X45	-0.019643	0.006810	-2.884
Nslp	-0.015334	0.005438	-2.820
FI	-0.005921	0.002879	-2.056

Na

Linear mixed model fit by REML

Formula: $\log(\text{Na}) \sim \text{WYear} + \text{Mean_Slope} + \text{X45} + \text{Nslp} + \text{Barren} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: Na

AIC	BIC	logLik	deviance	REMLdev
118.6	146.6	-48.3	48.64	96.59

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.20703422	0.455010	
	WYear	0.00035214	0.018765	-1.000
Year	(Intercept)	0.00186812	0.043222	
Residual		0.00638687	0.079918	

Number of obs: 94, groups: site_id, 74; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	3.312401	0.142034	23.321
WYear	-0.108411	0.023821	-4.551
Mean_Slope	0.009203	0.003678	2.502
X45	-0.017064	0.005232	-3.261
Nslp	-0.012933	0.004927	-2.625
Barren	-0.007560	0.002214	-3.414

Nitrate

Linear mixed model fit by REML

Formula: $\log(\text{Nitrate}) \sim \text{WYear} + \text{Mean_Slope} + \text{Barren} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: Nitrate

AIC	BIC	logLik	deviance	REMLdev
249	269.6	-115.5	209.7	231

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	1.5493e+00	1.2447e+00	
	WYear	2.5751e-02	1.6047e-01	-1.000
Year	(Intercept)	8.0009e-17	8.9448e-09	
Residual		3.4626e-01	5.8844e-01	

Number of obs: 73, groups: site_id, 59; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	-3.514599	0.434509	-8.089
WYear	0.288361	0.104436	2.761
Mean_Slope	0.019411	0.009572	2.028
Barren	0.027671	0.006549	4.225

PC

Linear mixed model fit by REML

Formula: $\log(\text{PC}) \sim \text{WYear} + \text{Park} + \text{WA} + \text{WA_3D} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: PC

AIC	BIC	logLik	deviance	REMLdev
188	213	-84.02	95.01	168

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.2071449	0.455132	
	WYear	0.0302451	0.173911	-0.743
Year	(Intercept)	0.0063267	0.079541	
Residual		0.0602344	0.245427	

Number of obs: 90, groups: site_id, 70; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	5.723e+00	1.335e-01	42.87
WYear	-1.133e-01	5.721e-02	-1.98
ParkY0SE	-2.976e-01	1.247e-01	-2.39
WA	7.925e-07	3.046e-07	2.60
WA_3D	-7.478e-07	2.758e-07	-2.71

pH

Linear mixed model fit by REML

Formula: $\log(\text{pH}) \sim \text{WYear} + \text{Max_Slope} + \text{X45} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: pH

AIC	BIC	logLik	deviance	REMLdev
-272.4	-249.3	145.2	-342.6	-290.4

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	6.7727e-05	0.0082297	
	WYear	4.9203e-05	0.0070145	1.000
Year	(Intercept)	4.5121e-06	0.0021242	
Residual		1.3538e-03	0.0367936	

Number of obs: 96, groups: site_id, 75; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	1.839e+00	1.036e-02	177.46
WYear	4.504e-03	3.899e-03	1.16
Max_Slope	5.489e-05	1.502e-05	3.66
X45	-1.626e-03	4.569e-04	-3.56

PN

Linear mixed model fit by REML

Formula: $\log(\text{PN}) \sim \text{WYear} + \text{Park} + \text{Z_Max} + \text{Z_Mean} + \text{Barren} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: PN2

AIC	BIC	logLik	deviance	REMLdev
221.7	249.7	-99.85	151.9	199.7

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.2223602	0.471551	
	WYear	0.0078548	0.088627	-0.634
Year	(Intercept)	0.0000000	0.000000	
Residual		0.1703150	0.412692	

Number of obs: 94, groups: site_id, 74; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	3.9518927	0.8558440	4.618
WYear	-0.1957180	0.0512353	-3.820
ParkYOSE	-0.6001794	0.1751018	-3.428
Z_Max	-0.0016350	0.0005635	-2.902
Z_Mean	0.0017278	0.0006523	2.649
Barren	-0.0099139	0.0037011	-2.679

PN_PP

Linear mixed model fit by REML

Formula: $\log(\text{PN_PP}) \sim \text{WYear} + \text{WYear2} + \text{Park} + \text{Barren} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: PN_PP

AIC	BIC	logLik	deviance	REMLdev
212.1	237.9	-96.06	177	192.1

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.92713	0.96287	
	WYear	0.16519	0.40643	-0.968
Year	(Intercept)	0.30070	0.54836	
Residual		0.10573	0.32517	

Number of obs: 97, groups: site_id, 75; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	2.471157	0.587629	4.205
WYear	1.758746	0.876299	2.007
WYear2	-0.742023	0.278452	-2.665
ParkYOSE	-0.579666	0.145846	-3.975
Barren	-0.006223	0.002306	-2.699

PP

Linear mixed model fit by REML

Formula: $\log(\text{PP}) \sim \text{WYear} + \text{WYear}^2 + \text{WYear}^3 + \text{Min_Slope} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: PP

AIC	BIC	logLik	deviance	REMLdev
159.9	185.5	-69.97	121.9	139.9

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.011902	0.10909	
	WYear	0.033806	0.18386	-1.000
Year	(Intercept)	0.017615	0.13272	
Residual		0.156892	0.39610	

Number of obs: 95, groups: site_id, 75; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	-1.74066	0.16198	-10.746
WYear	-0.46734	0.60371	-0.774
WYear ²	-0.65381	0.53725	-1.217
WYear ³	0.31518	0.11880	2.653
Min_Slope	0.02895	0.02227	1.300

Sulfate

Linear mixed model fit by REML

Formula: $\log(\text{Sulfate}) \sim \text{WYear} + \text{Z_Max} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: Sulfate

AIC	BIC	logLik	deviance	REMLdev
305.6	326.1	-144.8	270.9	289.6

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.643710	0.80232	
	WYear	0.080875	0.28439	-0.702
Year	(Intercept)	0.055947	0.23653	
Residual		0.577649	0.76003	

Number of obs: 96, groups: site_id, 75; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	-3.4638145	0.9107733	-3.803
WYear	0.1028399	0.1410684	0.729
Z_Max	0.0013418	0.0002412	5.563

SpecCond

Linear mixed model fit by REML

Formula: $\log(\text{SpCond}) \sim \text{WYear} + \text{WA} + \text{Max_Slope} + \text{X45} + \text{lake_area} + \text{WA_LA} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$ Data: SpCond

AIC BIC logLik deviance REMLdev
230.3 261.1 -103.2 120.3 206.3

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	2.0588e-01	4.5374e-01	
	WYear	2.8866e-03	5.3727e-02	-0.574
Year	(Intercept)	1.5655e-11	3.9567e-06	
Residual		8.5050e-02	2.9163e-01	

Number of obs: 96, groups: site_id, 75; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	2.384e+00	1.476e-01	16.152
WYear	-1.520e-01	3.937e-02	-3.860
WA	1.341e-07	4.712e-08	2.846
Max_Slope	4.764e-04	2.061e-04	2.312
X45	-1.572e-02	5.879e-03	-2.674
lake_area	-4.734e-02	1.497e-02	-3.162
WA_LA	-2.717e-03	1.035e-03	-2.627

TDN

Linear mixed model fit by REML

Formula: $\log(\text{TDN}) \sim \text{WYear} + \text{Park} + \text{Z_Mean} + \text{Min_Slope} + \text{FI} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: TDN

AIC BIC logLik deviance REMLdev
210 238.2 -94.01 147.8 188

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.0405908	0.201472	
	WYear	0.0081565	0.090314	1.000
Year	(Intercept)	0.0067626	0.082235	
Residual		0.1830031	0.427789	

Number of obs: 96, groups: site_id, 75; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	5.1310304	0.7269127	7.059
WYear	-0.1915578	0.0601829	-3.183
ParkYOSE	-0.8046452	0.1793889	-4.485
Z_Mean	-0.0007138	0.0001879	-3.799
Min_Slope	0.1048476	0.0309644	3.386
FI	-0.0068073	0.0027257	-2.497

TDP

Linear mixed model fit by REML

Formula: $\log(\text{TDP}) \sim \text{WYear} + \text{Nslp} + (1 \mid \text{Year}) + (1 + \text{WYear} \mid \text{site_id})$

Data: TDP

AIC BIC logLik deviance REMLdev

229.4 249 -106.7 201.2 213.4

Random effects:

Groups	Name	Variance	Std.Dev.	Corr
site_id	(Intercept)	0.000000	0.00000	
	WYear	0.028530	0.16891	NaN
Year	(Intercept)	0.056973	0.23869	
Residual		0.540720	0.73534	

Number of obs: 85, groups: site_id, 68; Year, 4

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	-2.961839	0.268983	-11.011
WYear	0.236484	0.136127	1.737
Nslp	-0.015317	0.007196	-2.128