EVALUATING WATERSHED MONITORING PROGRAMS

prepared for

Water Quality Management Office
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by

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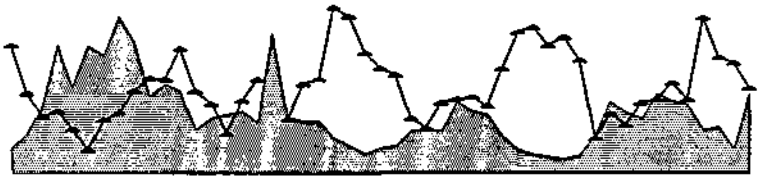
December 1988



ABSTRACT

The City of Baltimore has undertaken an intensive monitoring program to track changes in stream phosphorus loadings and reservoir conditions in response to watershed management efforts. Historical water quality and flow data from Loch Raven Reservoir and its watershed are analyzed to develop guidance for designing monitoring programs. Three topics are considered:

> **STREAM MONITORING.** Implementation of agricultural best management practices (BMP's) in the Piney Run subwatershed is accompanied by statistically significant ($p<.05$) reductions in the longterm average loadings of total phosphorus (27%, 32%), dissolved phosphorus (69%,27%) and suspended solids (60%,72%), as measured at two stream monitoring stations between 1982 and 1987. The observations suggest that the BMP's had measurable effects on nutrient and sediment loadings which are of importance with respect to management of Loch Raven Reservoir. The minimum detectable reduction in the longterm average loading varies with station, component, and sampling intensity. For historical monitoring program designs, minimum detectable reductions in average total phosphorus loading at two Piney Run stations are estimated to be 24-28%.
>
> **RESERVOIR MONITORING.** Spatial, seasonal, and yearly variations in phosphorus, chlorophyll-a, and transparency levels in Loch Raven Reservoir are characterized for 1984-1987. The longterm mean phosphorus concentration at Loch Raven Dam is estimated to be 27 +/- 4 ppb, as compared with the management objective of < 26 ppb. Unusually high variability in the reservoir phosphorus data hinders the detection of changes in longterm mean over time. Based upon historical monitoring frequencies and variance components at Loch Raven Dam, the probability of detecting a 28% change in the longterm mean phosphorus concentration occurring between two, four-year-long monitoring periods is estimated to be 33%, as compared with an 80% detection probability estimated for phosphorus variance components which are typical of other reservoir data sets.
>
> **LOAD/RESPONSE MODELING.** Mass-balance modeling indicates that year-to-year variability in average reservoir phosphorus concentrations largely reflect year-to-year variations in runoff and associated phosphorus loadings. Strong flow/concentration relationships observed in tributary streams are consistent with unusually high (~ 2X normal) phosphorus sedimentation rates estimated for Loch Raven Reservoir.

Based upon results of the analyses, recommendations for improving the efficiency and resolution of the watershed and reservoir monitoring programs are developed. Three supporting computer programs (**FLUX**, **LRSD.WK1**, and **CNET.WK1**) are provided to facilitate application of the analytical methods demonstrated in this report to data from other Baltimore watersheds and reservoirs.

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1.0 INTRODUCTION

The City of Baltimore and other regional governments are engaged in a watershed management program designed to protect/improve the quality of its water supply reservoirs (Baltimore City et al., 1984). Monitoring of tributary streams and reservoirs has been undertaken by the Baltimore City Water Quality Management Office (WQMO) to identify important pollutant source areas, quantify relationships between loadings and reservoir responses, and track the progress of watershed management efforts (Baltimore WQMO, 1985,1987,1988). Demonstrating statistically significant changes in water quality based upon monitoring data can be difficult because numerous sources of natural variability (particularly, climatologic factors) can obscure underlying trends.

Natural variability can be quantified through statistical analysis and modeling of historical data. Given adequate data, such exercises permit estimation of the following:

(1) precision of the annual and longterm means calculated for a given station, water quality component, and monitoring period (Walker, 1980, Smeltzer et al., 1988);

(2) minimum change the mean which is detectable (at a specified confidence level) for a given monitoring program design (Spooner et al., 1987; Smeltzer et al, 1988);

(3) "power" of a given monitoring program design, or the probability of detecting changes of specific magnitudes (Lettenmaier, 1976; Montgomery and Reckhow, 1984; Montgomery and Loftis, 1987);

(4) probability that a management objective, expressed in terms of a fixed target concentration for the longterm mean, has been achieved.

Such analyses may also identify important sources of variability and suggest improvements in monitoring program design to increase efficiency and to reduce the minimum detectable change for a fixed level of sampling effort.

This report applies the above concepts to historical monitoring data from Loch Raven Reservoir and its watershed. Management efforts for Loch Raven have been directed at achieving a mesotrophic status for the reservoir, as defined by a mean total phosphorus concentration less than 26 ppb. This target concentration is consistent with the objective of avoiding severe algal nuisance conditions and associated undesirable impacts on the water supply with respect to taste-and-odor, chlorinated organic materials, and treatment costs (Walker,1983). A similar target concentration (25 ppb) has been established for the St. Paul water supply lakes (Walker et al., 1988). Previous analyses (Stack and Gotfredson, 1980; Baltimore City WQMO, 1985, 1987) have indicated that achieving this objective would require a 28% reduction in the average reservoir concentration and watershed loading estimated prior to 1985. Of particular interest is the extent to which changes of this magnitude can be detected in the presence of natural and analytical variability.

The report analyzes water quality data supplied by the Baltimore WQMO and hydrologic data supplied by the U.S. Geological Survey for the 1982-1987 period. Major sections include:

2.0 ANALYSIS OF STREAM WATER QUALITY DATA - detecting changes in stream loadings following implementation of agricultural best management practices in the Piney Run watershed.

3.0 ANALYSIS OF RESERVOIR WATER QUALITY DATA - detecting changes in reservoir conditions for alternative monitoring program designs.

4.0 LOAD/RESPONSE MODELING - predicting yearly variations in reservoir conditions in response to yearly variations in hydrology and watershed loadings.

A final section summarizes conclusions and recommendations based upon study results.

2.0 ANALYSIS OF STREAM MONITORING DATA

The collection and analysis of stream flow and concentration data are critical to the following reservoir management efforts:

(1) quantifying annual and longterm average loadings of nutrients and other water quality components discharged from specific watersheds;

(2) constructing reservoir nutrient balances for use in eutrophication modeling;

(3) identifying "problem" watersheds (i.e., those with unusually high unit runoff or unit nutrient export rates in a given region) for possible implementation of point or nonpoint source controls;

(4) detecting load changes over time, attributed to changes in land use and/or implementation of source controls.

The potential importance of these applications can be considered in relation to the relative difficulty and expense involved in collecting representative data for use in load computations. Furthermore, there is no "standard" technique for reducing such data and application of different load computation techniques to a given data set will often yield results which are significantly different, both in a statistical sense and in a management sense. These considerations justify WQMO emphases on the collection and reduction of tributary monitoring data, as critical components of its watershed and reservoir management program.

This section describes and demonstrates statistical procedures which can be helpful in load computations. Specific applications include:

(1). estimating annual and longterm average loads and confidence limits for a given sampling station and water quality component;

(2) detecting step changes or trends in longterm average loads attributed to watershed management activities;

(3) designing monitoring programs to permit estimation of loads to a given precision or to permit detection of changes of a given magnitude.

Methods, data sets, and results are described below.

2.1 FLUX Program

FLUX (Walker, 1987) is a computer program developed specifically for estimating stream loads or mass discharges required for constructing reservoir or lake nutrient balances. The program interprets water quality and flow information derived from grab or composite samples to estimate the mean (or total) loading over the complete flow record between two dates. Since the appropriate loading calculation method depends partially upon the concentration/flow dynamics characteristic of a given station and component and on the sampling program design, seven alternative calculation methods are provided. These methods have been tested extensively and shown to yield unbiased predictions with minimum variance, provided certain criteria are met. An option to stratify the samples into groups based upon flow, date, and/or season is also included. In many cases, stratifying the sample increases the accuracy and reduces potential biases in loading estimates. The jackknife technique (Mosteller and Tukey, 1978) is used to calculate the error variances of mean loading estimates. A variety of graphic and statistical diagnostics help the user to evaluate data adequacy and select the most appropriate calculation method and stratification scheme for a given data set. **FLUX** also provides information which can be useful for designing stream sampling programs, specifically with respect to optimal allocation of sampling effort among flow strata.

The original mainframe version of **FLUX** (Walker, 1987) has been adapted for use on IBM-PC compatible microcomputers (Version 3.0). The program has been subsequently revised to provide a number of features necessary for WQMO applications. Version 4.2 of the program and documentation are provided separately for use by WQMO staff (Walker, 1988). Specific enhancements important for WQMO applications include:

(1) optional specification of continuous flow record as a frequency distribution table (vs. daily mean flows); this facilitates use of 15-minute unit flow measurements;

(2) algorithms for detecting trends or step changes in loadings;

(3) improved accuracy of error analysis calculations for data sets containing multiple discrete samples within storm events (jackknifing by event vs. sample to reduce serial correlation);

(4) estimation of load time series at daily, monthly, or annual frequencies.

Version 4.2 also has an expanded user interface (menu structure, help screens), alternative input file formats (original **FLUX**, ASCII, LOTUS-123), and high-resolution graphics (compatible with the IBM Enhanced Graphics Adaptor).

2.2 Stream Data Sets

The WQMO has provided three stream data sets for intensive study. Stations include:

PIU0016 - Piney Run at Butler Road (Drainage Area = 31.9 km^2)

PIU0030 - Yohn's Farm (Drainage Area = .3 km^2)

STP8005 - Hampstead Wastewater Treatment Plant

Station locations are shown in Figure 1. All of these stations are located in the Piney Run watershed, a 31.9 km^2 tributary of Western Run, which supplies Loch Raven Reservoir. Stream flow and concentration data are inventoried in Table 1. The data sets generally span the period from late 1982 to early 1988.

The Farm station is located on a small tributary of Piney Run, immediately below a feedlot which was equipped with animal waste storage facilities in December of 1986. The effects of these facilities on watershed loadings are evaluated below by comparing stream data collected before and after December 1986. The Butler Road station is located near the mouth of the watershed and reflects the aggregate impacts of all watershed sources and activities. The Hampstead WWTP is located near the headwaters of Piney Run (Figure 1). The treatment facility was upgraded in 1984-1985 (phosphorus removal, nitrification). Analysis of the WWTP data is required to permit interpretation of observed changes in loading at the Butler Road station (in particular, to distinguish between changes in point-source and nonpoint-source loads).

One important objective of the analysis is to determine the extent to which significant reductions in nutrient loading can be detected at the Butler Road station as a result of the implementation of agricultural best management practices in the Piney Run watershed. Most of the practices were implemented during 1982 and 1983 (Table 2) on areas up to 569 acres (vs. total watershed area of 7,877 acres). The effects of these practices on total watershed loadings would depend upon their onsite effectiveness and upon the extent to which the treated areas include all of the critical source areas in the watershed. Dividing the Butler Road data set into two periods (5/18/82 to 9/1/84 and 9/1/84 to 1/19/88) provides a basis for comparing watershed loadings measured during and

Figure 1
Piney Run Sampling Stations

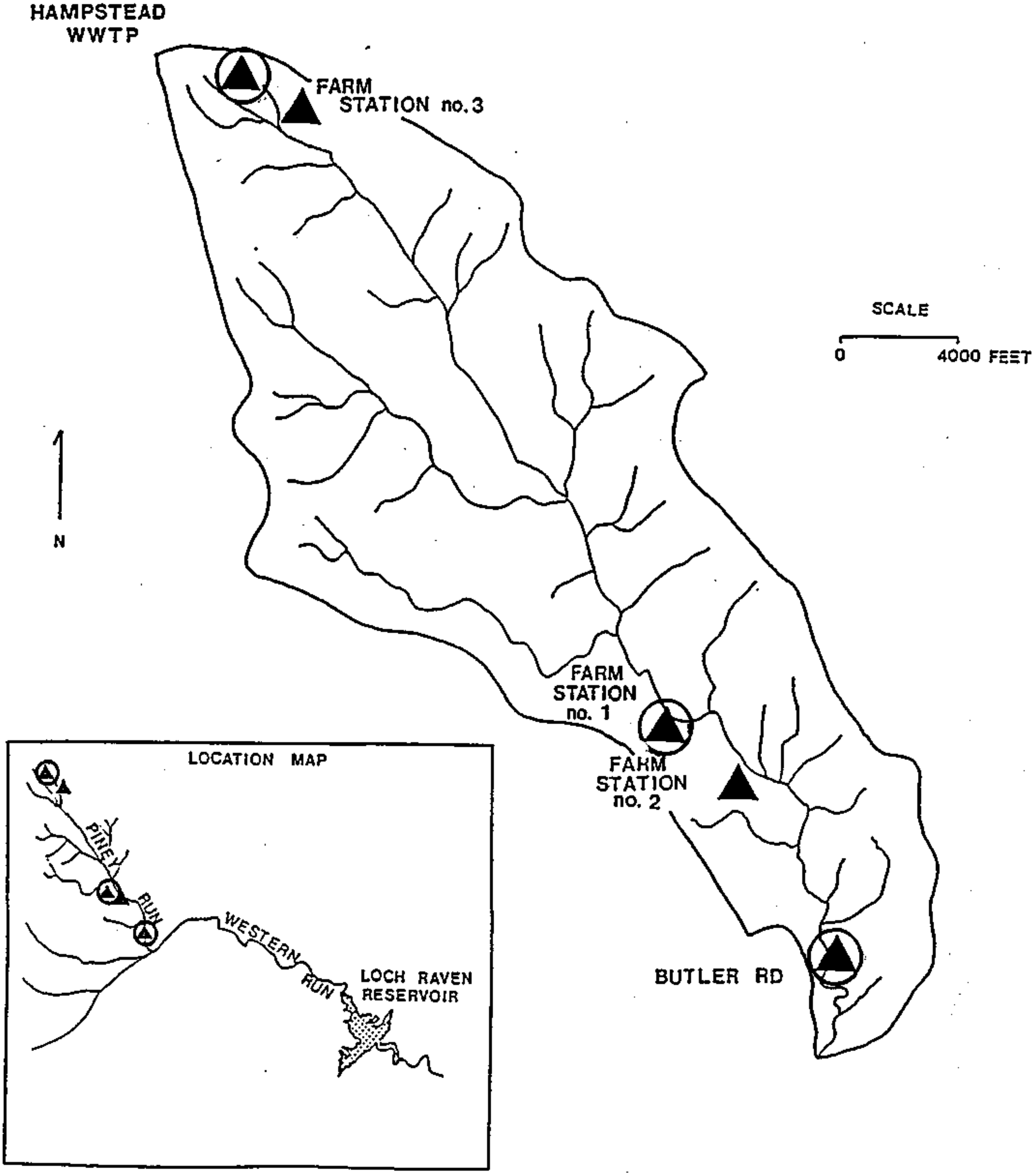


Table 1
Piney Run Station Descriptions

Station: Piney Run at Butler Road Station Code: PIU0016

Drainage Area: 31.9 km^2
Sample Dates: 05/18/82 to 01/19/88
Flow Station Code: 01583100
Flow Dates: 05/10/82 to 09/30/87 Days: 1928
Mean Flow: 12.14 hm^3/yr = 0.385 m^3/sec
Flow Strata Boundaries: 10 and 50 hm^3/yr

Year:	1982	1983	1984	1985	1986	1987	1988
Samples:	57	83	41	14	18	47	7

Critical Dates: ~09/01/84 after most BMP installation & Hampstead WWTP phosphorus removal

Station: Yohn's Farm Station Code: PIU0030

Drainage Area: 0.3 km^2
Sample Dates: 12/12/83 to 01/25/88
Flow Station Code:
Flow Dates: 01/25/84 to 12/31/87 Days: 1367
Mean Flow: 0.11 hm^3/yr = 0.0035 m^3/sec
Flow Strata Boundary: .3 hm^3/yr

Year:	1982	1983	1984	1985	1986	1987	1988
Samples:	0	7	65	27	14	62	5

Critical Dates: ~12/01/86 animal waste storage facility

Station: Hampstead WWTP Station Code: STP8005

Sample Dates: 09/29/82 to 01/25/88
Mean Flow: 0.32 hm^3/yr = 0.0101 m^3/sec

Year:	1982	1983	1984	1985	1986	1987	1988
Samples:	30	40	33	30	23	23	1

Critical Dates: ~08/01/84 phosphorus removal
~01/01/86 nitrification

Table 2
BMP Implementation in the Piney Run Watershed

		Year of Implementation					
Management Practice		1982	1983	1984	1985	1986	1987
Conservation Cropping	Acres	407	38	0	0	0	0
Conservation Tillage	Acres	404	38	0	0	0	0
Contour Farming	Acres	113	0	0	0	0	0
Cover Crops	Acres	99	0	0	0	0	0
Critical Area Planting	Acres	0	0	1	3	0	0
Crop Residue Use	Acres	346	38	0	0	0	0
Pasture Management	Acres	287	143	221	162	0	0
Soil Testing	Acres	569	0	0	0	0	0
Strip Cropping	Acres	139	184	0	18	0	0
Integrated Pest Mgt.	Acres	139	90	0	0	0	0
Animal Waste Mgt.	No.	2	0	0	1	2	0
Fencing	Feet	0	700	0	8500	0	0
Grassed Waterways	Feet	200	1500	1050	1150	0	0
Spring Development	No.	1	1	4	2	0	0
Sediment Basins	No.	0	0	0	1	0	0
Water Control Struc.	No.	2	3	0	3	0	0

after the period of BMP implementation. Available data do not permit a true "before" and "after" comparison. The 9/1/84 dividing date is also convenient because it divides the data set roughly in half and corresponds approximately to the implementation of phosphorus removal at the Hampstead WWTP (approx. 8/1/84).

2.3 Exploratory Analysis

The Piney Run data analysis focuses on the following water quality components which were included in the monitoring program:

Total Phosphorus
Total Dissolved Phosphorus
Total Suspended Solids
Ammonia Nitrogen
Nitrate + Nitrite Nitrogen

Sampling frequencies for Total Kjeldahl Nitrogen, also of significance from a reservoir (and Chesapeake Bay) water quality management perspective, were insufficient to support statistical analysis over both time periods at these stations.

Calculations of mass discharge or flux depend critically upon the relationship between flow and concentration. Log-scale scatter plots for each variable are shown in the following Figures:

2 Conc. vs. Flow Relationships - Farm Station
3 Conc. vs. Flow and Residuals vs. Date - Farm Station
4 Conc. vs. Flow Relationships - Piney Run
5 Conc. vs. Flow and Residuals vs. Date - Piney Run

Displays of this type are generated by FLUX for use in exploratory data analysis. As illustrated in these figures, there are two basic approaches to detecting trends or step changes in the flow/ concentration relationship at the exploratory stage:

Figure 2
Concentration vs. Flow Relationships - Farm Station

STRAT-1: Date <= 86/12/01   STRAT-2: Date > 86/12/01

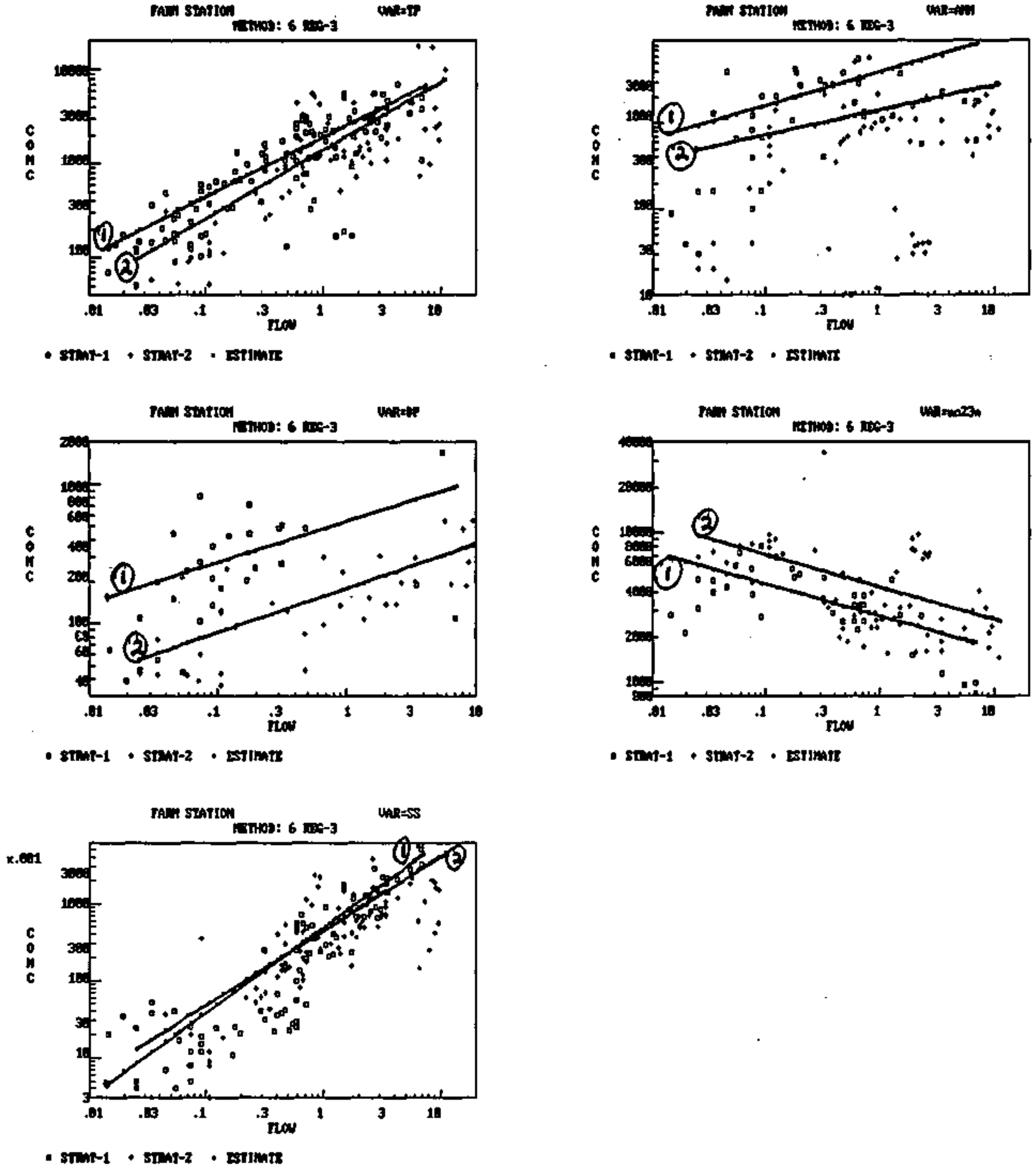


Figure 3
Concentration vs. Flow and Residuals vs. Date - Farm Station

STRAT-1: Low-Flow STRAT-2: High-Flow

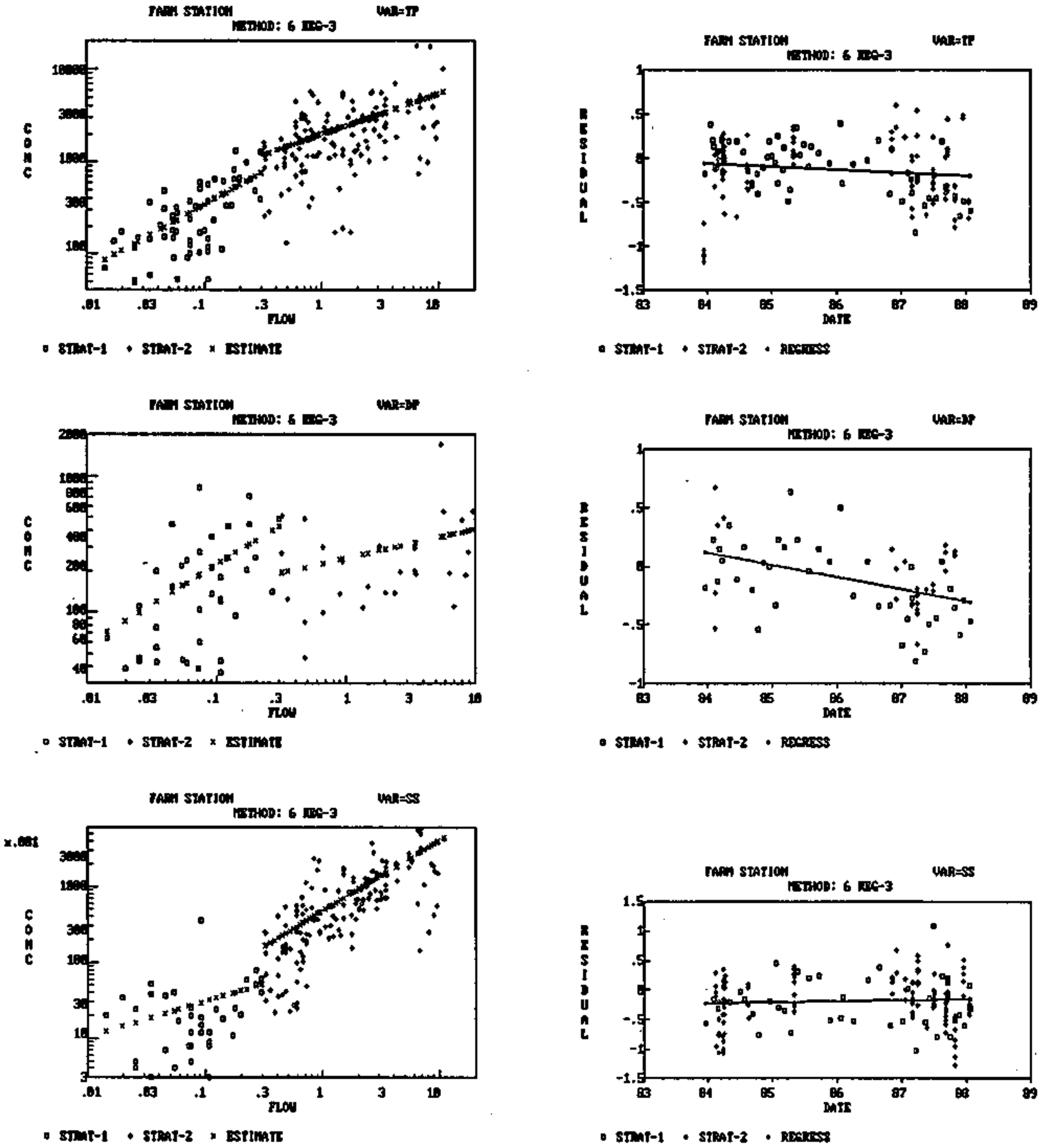


Figure 3 (ct)
Concentration vs. Flow and Residuals vs. Date - Farm Station

STRAT-1: Low-Flow   STRAT-2: High-Flow

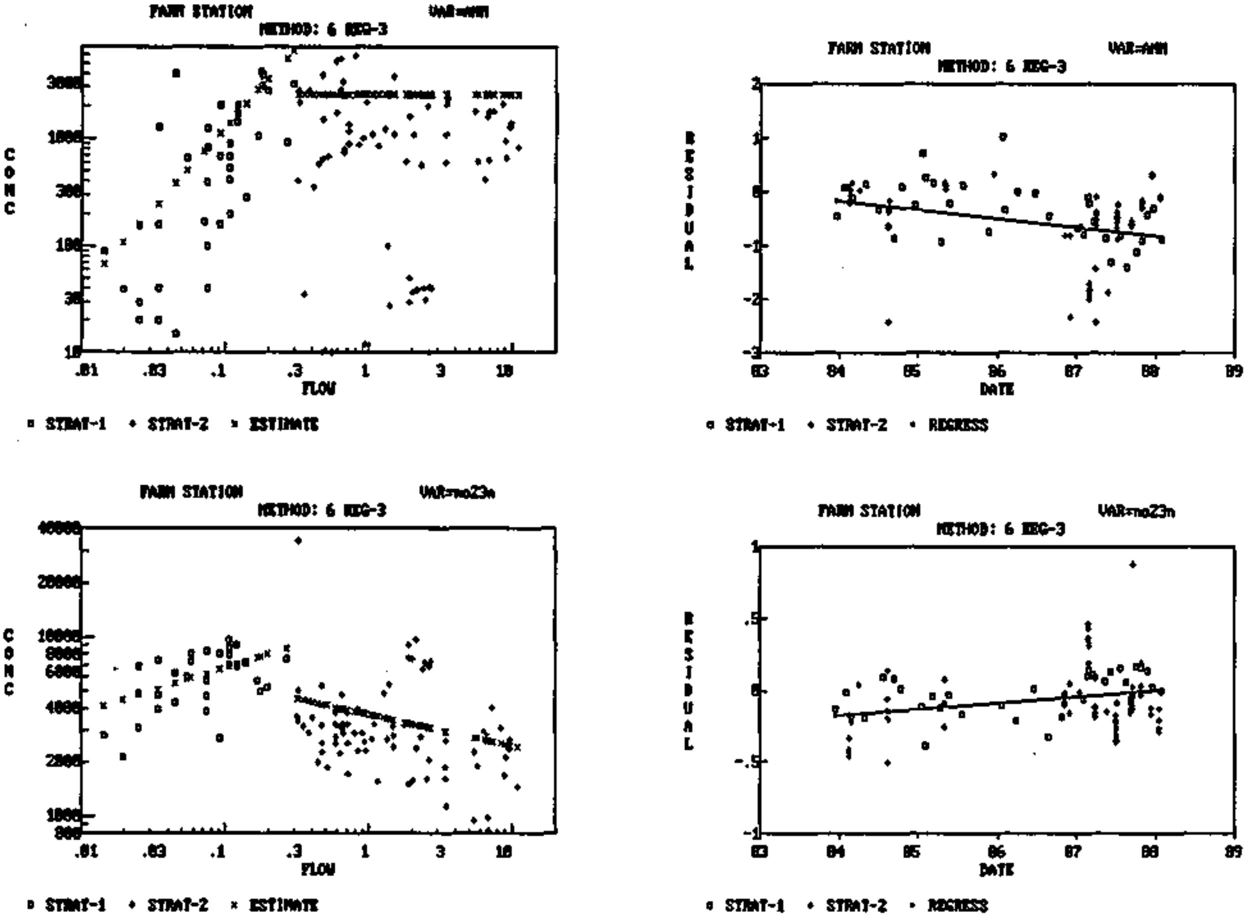


Figure 4
Concentration vs. Flow Relationships - Piney Run

STRAT-1: Date <= 84/09/01   STRAT-2: Date > 86/09/01

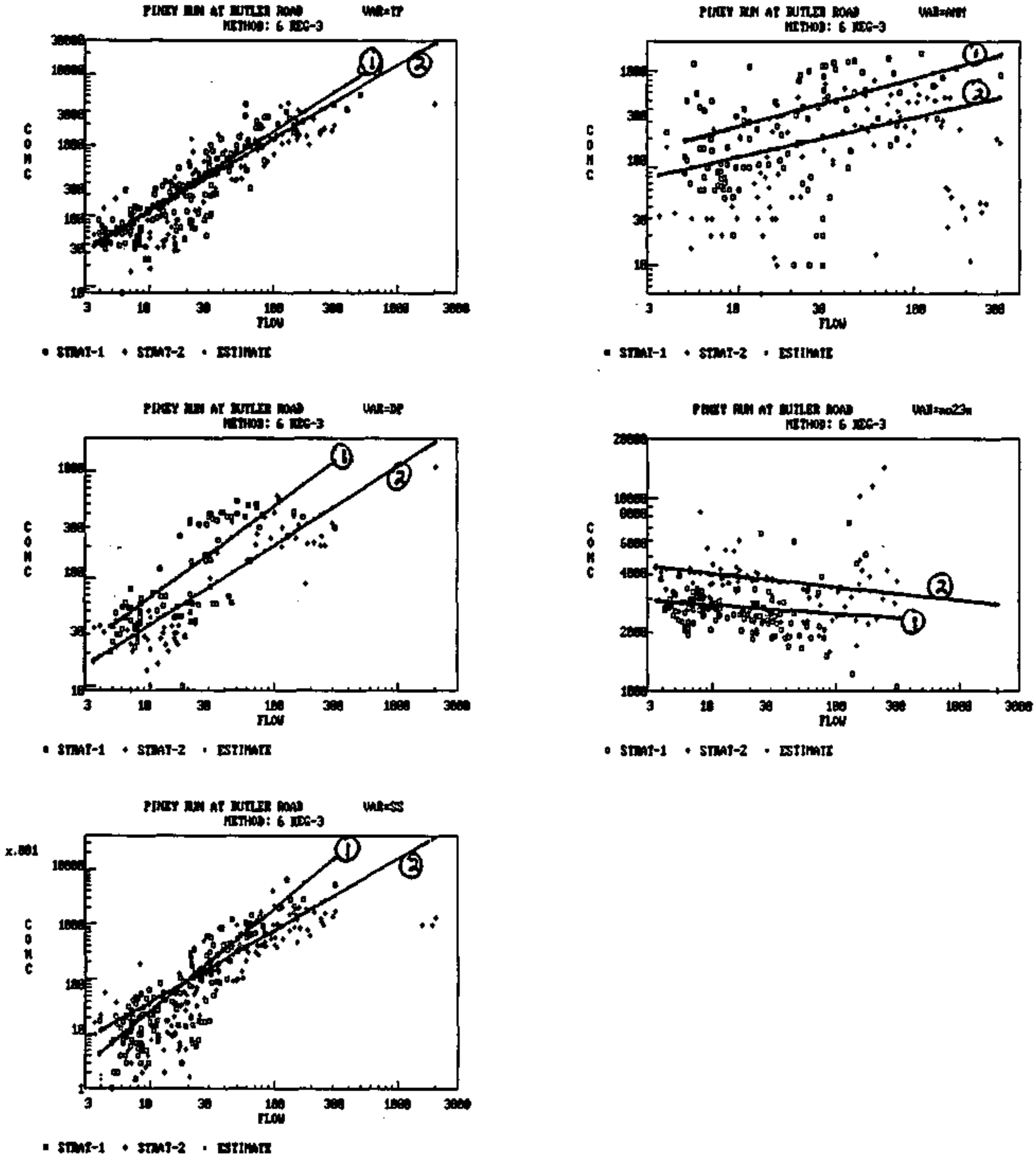


Figure 5
Concentration vs. Flow and Residuals vs. Date - Piney Run

STRAT-1: Low-Flow STRAT-2: Medium-Flow STRAT-3: High-Flow

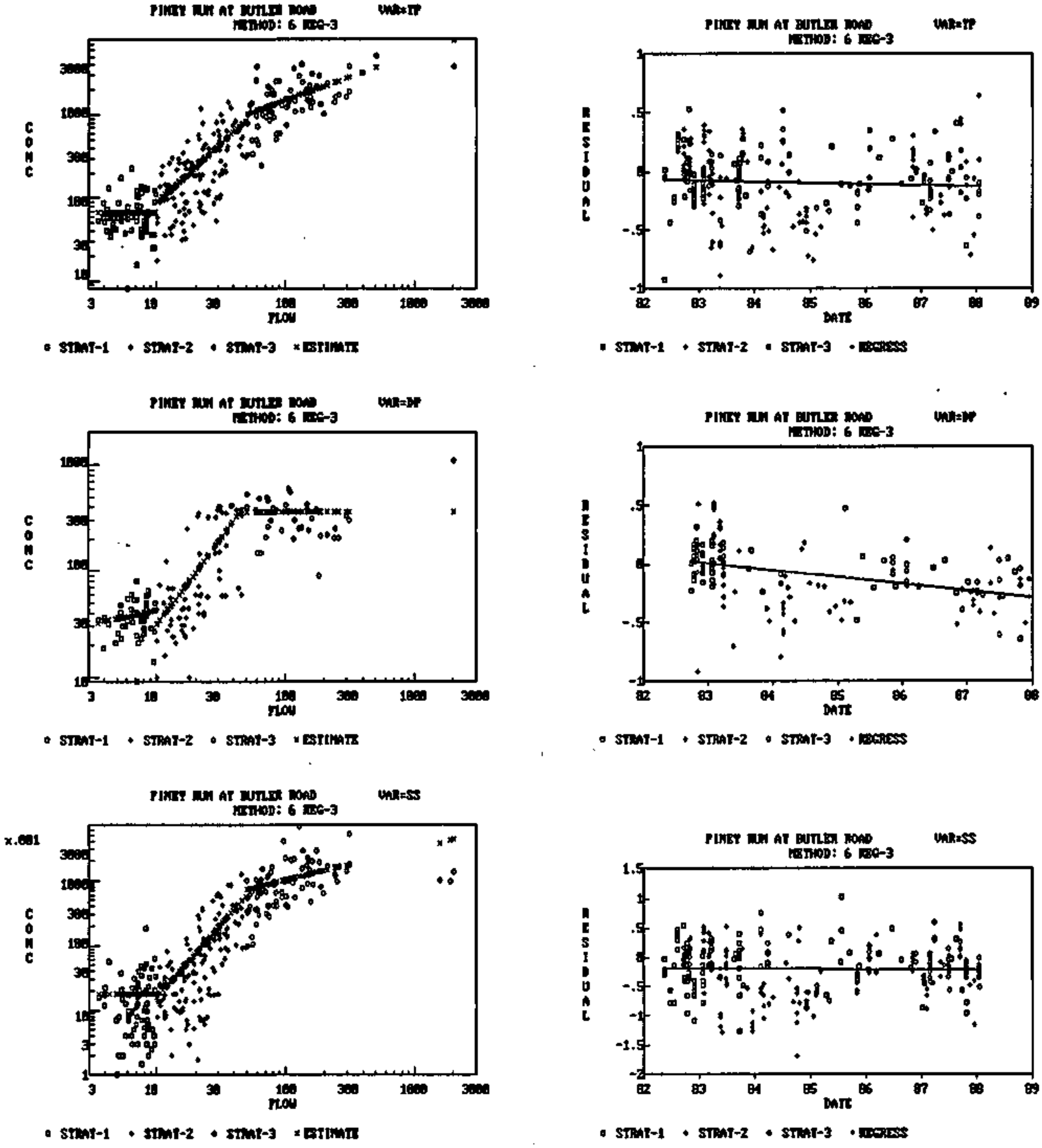
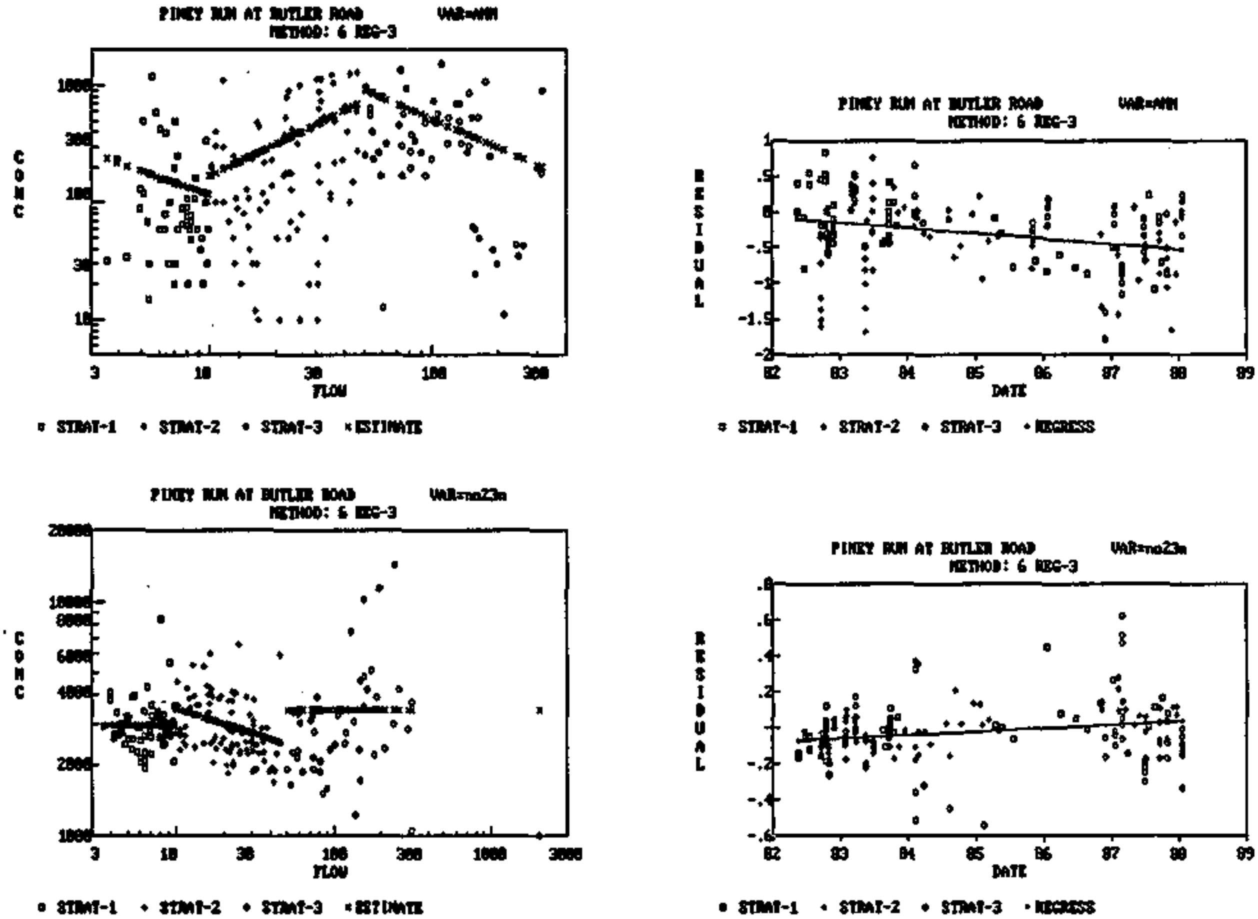


Figure 5 (ct)
Concentration vs. Flow and Residuals vs. Date - Piney Run

STRAT-1: Low-Flow STRAT-2: Medium-Flow STRAT-3: High-Flow



(A) Divide the data set into two groups or strata based upon date and fit separate log(c) vs. log(q) regressions for each group. Changes in the watershed response are roughly depicted by separation of the regression lines ("1" and "2") in Figures 2 and 4.

(B) Divide the data set into two or three strata based upon flow range, fit a separate log(c) vs. log(q) regression equation for each stratum, and plot residuals (log(observed conc.) - log (predicted conc.)) vs. date. Changes in the flow/concentration relationship are revealed by slopes of the residual vs. date regression lines in Figures 3 and 5.

The exploratory plots generally indicate strong flow/concentration relationships in these streams for suspended solids and total phosphorus. This primarily reflects the fact that high flow velocities are required to transport particulate materials downstream. Flow/concentration relationships are weaker and more variable for dissolved species (dissolved phosphorus, ammonia, nitrate + nitrite nitrogen).

The slopes of the total phosphorus regression lines in Figures 2 and 4, range from .67 to 1.0 for total phosphorus. In comparison, Walker (1981) found a slope range of -.4 to .75 in nationwide data from 86 reservoir tributary stations (median ~ .05, 90th percentile ~.4). The relatively strong concentration vs. flow relationships in Piney Run streams may reflect watershed geologic, topographic, and land use characteristics. Watershed maps (Figure 1) also suggest high stream drainage densities (stream lengths per unit area), which would promote transport of sediment, phosphorus, and other water quality components originating in surface runoff.

Changes in the flow/concentration relationship over time are more readily apparent for dissolved phosphorus and ammonia than for the other components (e.g., based upon the separations of the regression lines in Figures 2 and 4 upon the residual trends in Figures 3 and 5). Concentrations of dissolved species would be sensitive to point sources and to animal waste management practices, particularly under low flows. Possible impacts of watershed erosion controls on particulate loadings are suggested by the lower concentrations of total phosphorus and suspended solids under high-flow conditions (comparing symbols in Figures 2 and 4). These changes are analyzed from a statistical point of view in the confirmatory analyses below (see 2.5 Load Contrasts).

Exploratory displays of loading data from the Hampstead WWTP are shown in Figure 6. As is typical of point sources, the relationship between flow and concentration is weak at this station and the data are most usefully summarized as load time series (using FLUX Model 1). Three time periods are identified (as indicated in Table 1) to reflect changes in treatment (phosphorus removal in late 1984 and nitrification in late 1985). The horizontal lines in Figure 6 show the average loadings calculated for each time period and component in relation to the individual measurements.

2.4 Flow Frequency Distributions

Calculation of longterm average loads for a given stream station and water quality component involves mapping the flow/concentration relationship developed from sampling data onto the flow frequency distribution for that station. Flow frequency distributions calculated for each station based upon 15-minute unit values and daily mean values are summarized in Table 3 (Farm Station) and Table 4 (Piney Run at Butler Road).

When strong flow/concentration relationships are encountered, especially in flashy streams, it is important to develop the flow frequency distributions from 15-minute unit values. Using daily values underestimates the frequencies of extreme high flows which may account for a high fraction of the total volume and loading. Figure 7 shows the theoretical biases associated with using daily mean flows in calculating loads at each station as a function of the log(c) vs. log(q) slope. These curves have been developed by integrating linear log(c) vs. log(q) equations with slopes ranging from -1.0 to 1.5 along the volume frequency

Figure 6
Load vs. Date - Hampstead WWTP

STRAT-1: <= 84/8/1, STRAT-2: 84/8/1 < D <= 86/1/1, STRAT 3: > 86/1/1

LOAD in KG/YR

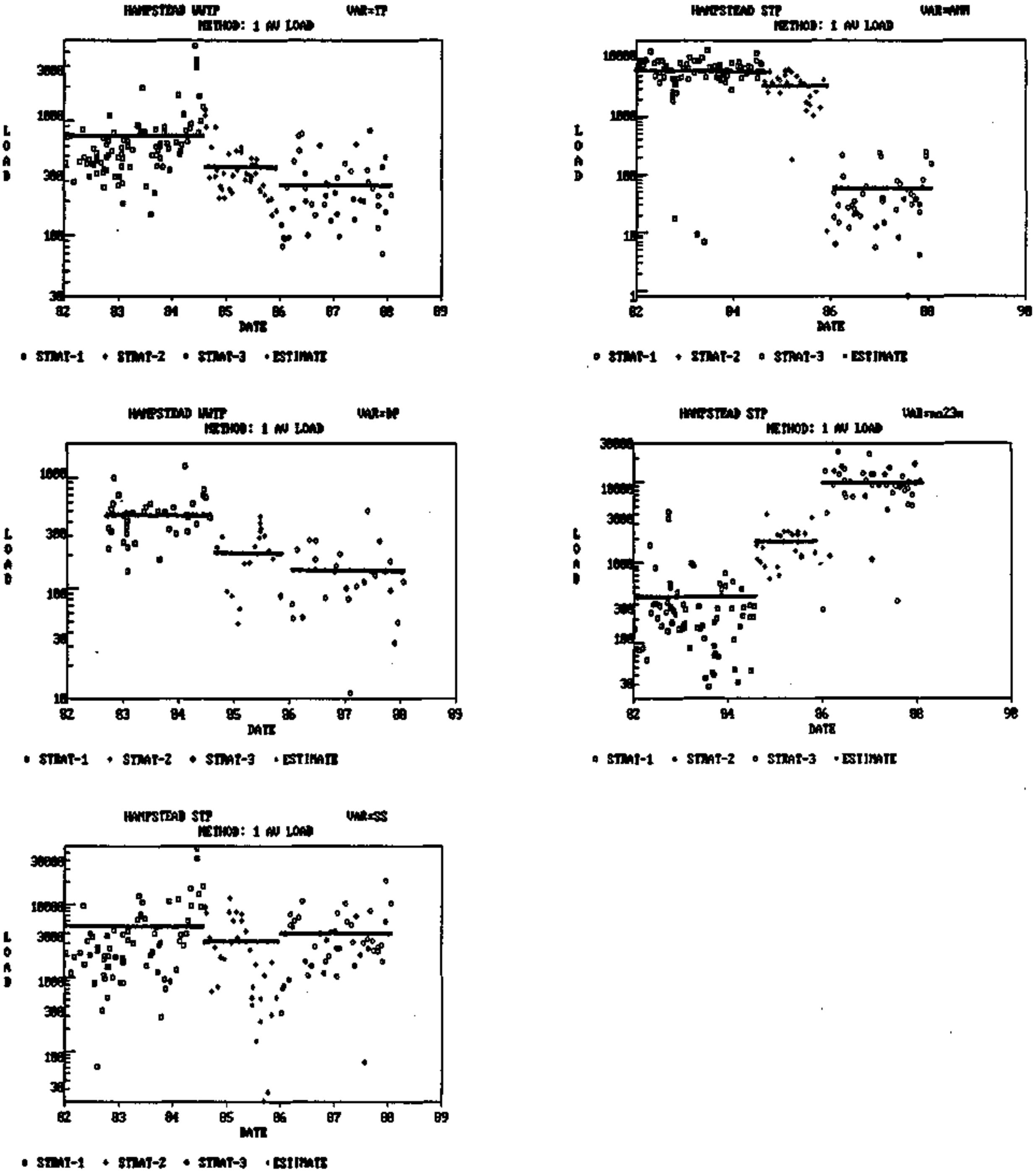


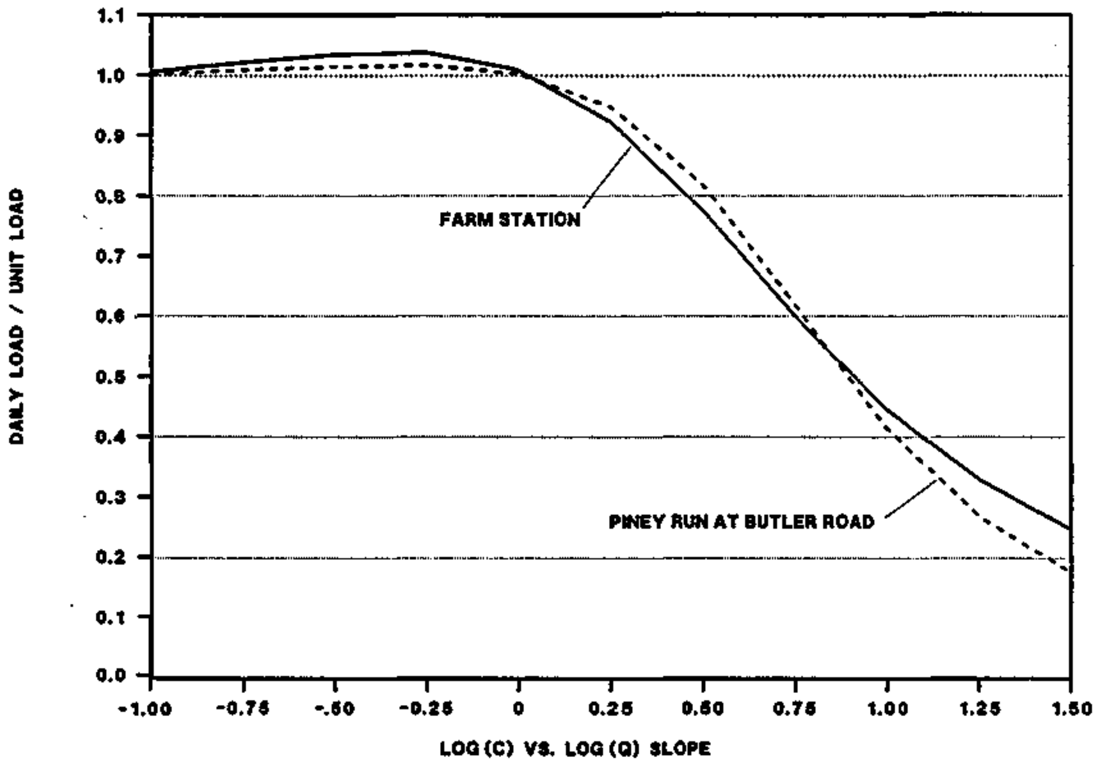
Table 3
Farm Station Flow Frequency Distributions

		----- 15-Minute Unit Values ------				-------- Daily Mean Values --------			
Inc	Qmax hm3/yr	Count	Cum. Count	Volume m3	Cum. Volume m3	Count	Cum. Count	Volume m3	Cum. Volume m3
1	0.004	262	262	24.9	25	0	0	0.0	0
2	0.004	13	275	1.5	26	1	1	11.3	11
3	0.005	119	394	15.9	42	0	1	0.0	11
4	0.006	148	542	22.9	65	1	2	15.1	26
5	0.007	96	638	17.4	83	2	4	35.6	62
6	0.008	1517	2155	344.9	428	2	6	38.0	100
7	0.010	168	2323	41.9	469	5	11	119.5	220
8	0.011	380	2703	113.9	583	7	18	202.3	422
9	0.013	477	3180	163.5	747	23	41	764.8	1187
10	0.016	6766	9946	2766.0	3513	48	89	1920.1	3107
11	0.018	8573	18519	4150.1	7663	87	176	4056.0	7163
12	0.022	9656	28175	5440.4	13103	92	268	5012.2	12175
13	0.026	10738	38913	7421.0	20524	88	356	5671.3	17846
14	0.030	695	39608	562.0	21086	39	395	2949.2	20795
15	0.035	9666	49274	9345.4	30432	67	462	6103.7	26899
16	0.042	803	50077	880.7	31313	44	506	4649.6	31549
17	0.049	9925	60002	12671.3	43984	78	584	9660.0	41209
18	0.058	924	60926	1401.2	45385	49	633	7230.7	48439
19	0.068	8389	69315	14003.7	59389	70	703	11848.2	60288
20	0.080	3239	72554	6855.3	66244	55	758	11148.4	71436
21	0.095	13779	86333	36090.6	102335	108	866	26660.4	98096
22	0.112	8516	94849	25750.6	128085	83	949	23588.5	121685
23	0.131	8381	103230	29265.3	157351	100	1049	33231.5	154917
24	0.155	5560	108790	22246.1	179597	73	1122	28410.9	183327
25	0.182	6116	114906	29712.5	209309	60	1182	27534.3	210862
26	0.215	3092	117998	17464.5	226774	41	1223	22377.4	233239
27	0.253	3712	121710	24133.4	250907	31	1254	19709.8	252949
28	0.298	2950	124660	23339.6	274247	28	1282	21220.1	274169
29	0.351	1703	126363	16083.2	290330	23	1305	20299.2	294468
30	0.414	910	127273	10197.0	300527	19	1324	19742.2	314210
31	0.488	782	128055	10107.2	310634	9	1333	11260.4	325471
32	0.575	444	128499	6626.6	317261	8	1341	11965.4	337436
33	0.677	433	128932	7740.3	325001	4	1345	7082.4	344519
34	0.798	171	129103	3561.1	328562	5	1350	10090.8	354609
35	0.940	305	129408	7497.4	336059	6	1356	14473.1	369082
36	1.107	160	129568	4575.9	340635	1	1357	2651.7	371734
37	1.304	186	129754	6200.7	346836	3	1360	9964.3	381698
38	1.536	137	129891	5581.5	352417	2	1362	7789.2	389488
39	1.810	117	130008	5514.7	357932	1	1363	4309.7	393797
40	2.132	79	130087	4442.6	362375	1	1364	5829.8	399627
41	2.511	112	130199	7493.4	369868	1	1365	6040.1	405667
42	2.958	37	130236	2859.3	372727	0	1365	0.0	405667
43	3.485	44	130280	4035.1	376763	0	1365	0.0	405667
44	4.106	35	130315	3763.5	380526	1	1366	10880.5	416548
45	4.837	29	130344	3745.3	384271	1	1367	12555.1	429103
46	5.698	27	130371	4012.5	388284	0	1367	0.0	429103
47	6.713	21	130392	3643.4	391927	0	1367	0.0	429103
48	7.908	23	130415	4713.3	396641	0	1367	0.0	429103
49	9.316	20	130435	4932.4	401573	0	1367	0.0	429103
50	10.975	77	130512	23767.1	425340	0	1367	0.0	429103

Table 4
Piney Run at Butler Road Flow Frequency Distributions

		15-Minute Unit Values				Daily Mean Values			
Inc	Qmax hm3/yr	Count	Cum. Count	Volume 1000 m3	Cum. Volume 1000 m3	Count	Cum. Count	Volume 1000 m3	Cum. Volume 1000 m3
1	2.2	33	33	2.0	2	0	0	0.0	0
2	2.6	424	457	29.6	32	3	3	19.9	20
3	3.0	989	1446	79.5	111	11	14	84.8	105
4	3.5	4348	5794	405.3	516	41	55	368.0	473
5	4.0	6410	12204	685.9	1202	70	125	720.1	1193
6	4.6	7253	19457	881.7	2084	78	203	918.6	2111
7	5.4	13047	32504	1856.6	3941	124	327	1703.6	3815
8	6.2	15443	47947	2524.1	6465	162	489	2551.8	6367
9	7.2	15059	63006	2883.0	9348	147	636	2715.2	9082
10	8.3	17651	80657	3952.4	13300	159	795	3379.5	12462
11	9.6	16993	97650	4273.1	17573	216	1011	5269.7	17731
12	11.2	24519	122169	7265.0	24838	224	1235	6406.4	24138
13	12.9	15616	137785	5339.8	30178	159	1394	5192.7	29330
14	14.9	10835	148620	4265.9	34444	146	1540	5547.8	34878
15	17.3	12565	161185	5708.6	40153	102	1642	4437.4	39315
16	20.0	7409	168594	3962.6	44115	81	1723	4127.4	43443
17	23.2	3987	172581	2409.6	46525	66	1789	3879.8	47323
18	26.8	4581	177162	3179.1	49704	46	1835	3121.7	50444
19	31.0	1975	179137	1602.2	51306	18	1853	1420.4	51865
20	35.9	1552	180689	1473.5	52779	23	1876	2085.1	53950
21	41.5	773	181462	848.9	53628	15	1891	1572.5	55522
22	48.1	668	182130	843.4	54472	10	1901	1217.2	56739
23	55.6	564	182694	830.6	55302	5	1906	706.3	57446
24	64.4	454	183148	782.3	56085	6	1912	967.9	58414
25	74.5	320	183468	633.1	56718	6	1918	1169.8	59583
26	86.3	323	183791	737.5	57455	4	1922	873.9	60457
27	99.8	214	184005	564.3	58019	1	1923	266.6	60724
28	115.5	161	184166	494.7	58514	1	1924	310.5	61034
29	133.7	113	184279	397.9	58912	1	1925	334.4	61369
30	154.8	93	184372	382.4	59294	0	1925	0.0	61369
31	179.1	85	184457	403.3	59698	0	1925	0.0	61369
32	207.3	44	184501	241.1	59939	0	1925	0.0	61369
33	239.9	34	184535	213.2	60152	0	1925	0.0	61369
34	277.7	34	184569	248.3	60400	2	1927	1335.4	62704
35	321.4	25	184594	210.6	60611	0	1927	0.0	62704
36	372.0	35	184629	343.8	60955	0	1927	0.0	62704
37	430.5	12	184641	139.1	61094	0	1927	0.0	62704
38	498.2	13	184654	170.7	61265	0	1927	0.0	62704
39	576.6	17	184671	260.4	61525	1	1928	1467.7	64172
40	667.4	10	184681	176.7	61702	0	1928	0.0	64172
41	772.4	10	184691	209.1	61911	0	1928	0.0	64172
42	893.9	4	184695	95.9	62007	0	1928	0.0	64172
43	1034.6	7	184702	193.3	62200	0	1928	0.0	64172
44	1197.4	6	184708	189.5	62390	0	1928	0.0	64172
45	1385.8	6	184714	227.2	62617	0	1928	0.0	64172
46	1603.9	5	184719	216.3	62833	0	1928	0.0	64172
47	1856.3	8	184727	400.2	63233	0	1928	0.0	64172
48	2148.4	10	184737	562.1	63795	0	1928	0.0	64172
49	2486.5	1	184738	66.3	63862	0	1928	0.0	64172
50	2877.7	2	184740	154.3	64016	0	1928	0.0	64172

Figure 7
Effect of Flow Averaging Interval on Load Estimates for Various C vs. Q Relationships



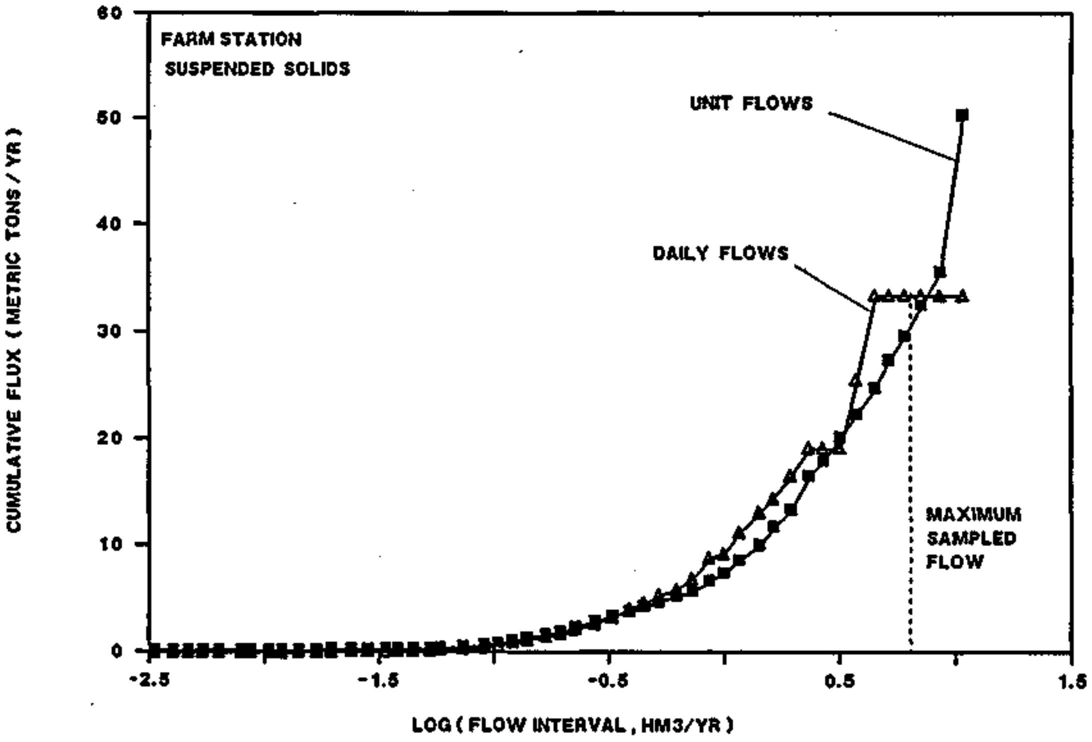
distributions (Tables 3 and 4). There is little difference between the two stations in this respect, apparently because the relative magnitudes of the within-day vs. among-day flow variations are similar.

Figure 8 compares longterm average flux estimates developed from unit flows vs. daily flows at the Farm station for suspended solids, total phosphorus, and dissolved phosphorus. Figure 9 shows corresponding curves for Piney Run at Butler Road. These curves have been developed by fitting a fourth degree polynomial to the log(c) vs. log(q) relationship (using **FLUX** Model 7) for each station and component (all sampled dates and flows) and integrating along the unit and daily volume frequency distributions (using **FLUX** "Utilities List Table" procedure). The "Maximum Sampled Flow" indicated in these figures refers to the maximum flow sampled during both time periods at each station.

At both stations, the bias associated with using daily flows is insignificant for dissolved phosphorus over the entire flow range. The bias is also insignificant for total phosphorus and suspended solids over the range flows which were sampled during both periods of interest (< "Maximum Sampled Flow"). Negative biases on the order of 20-35% are encountered when the entire flow range is considered for total phosphorus and suspended solids. Based upon the frequency distributions in Tables 3 and 4, flows exceeding the maximum sampled flows are extremely infrequent (<.1% of the time at the Farm Station and <.05% of the time at Piney Run). The probability of actually sampling flows in these ranges is exceedingly small. Differences in load estimates developed from unit flows vs. daily mean flows must rely upon extrapolation of the flow/concentration relationship into an unmonitored or sparsely monitored flow range.

Although the "theoretical" analysis (Figure 7) suggests more serious biases, these do not occur because the slopes of the flow/concentration relationships at these stations decrease in higher flow ranges (Figures 2-5). Another important factor is that reservoir eutrophication response is much more sensitive to the dissolved phosphorus load than to the particulate phosphorus load. Dissolved P load calculations are

Figure 8
Load Estimate Comparisons - Unit vs. Daily Flows - Farm Station



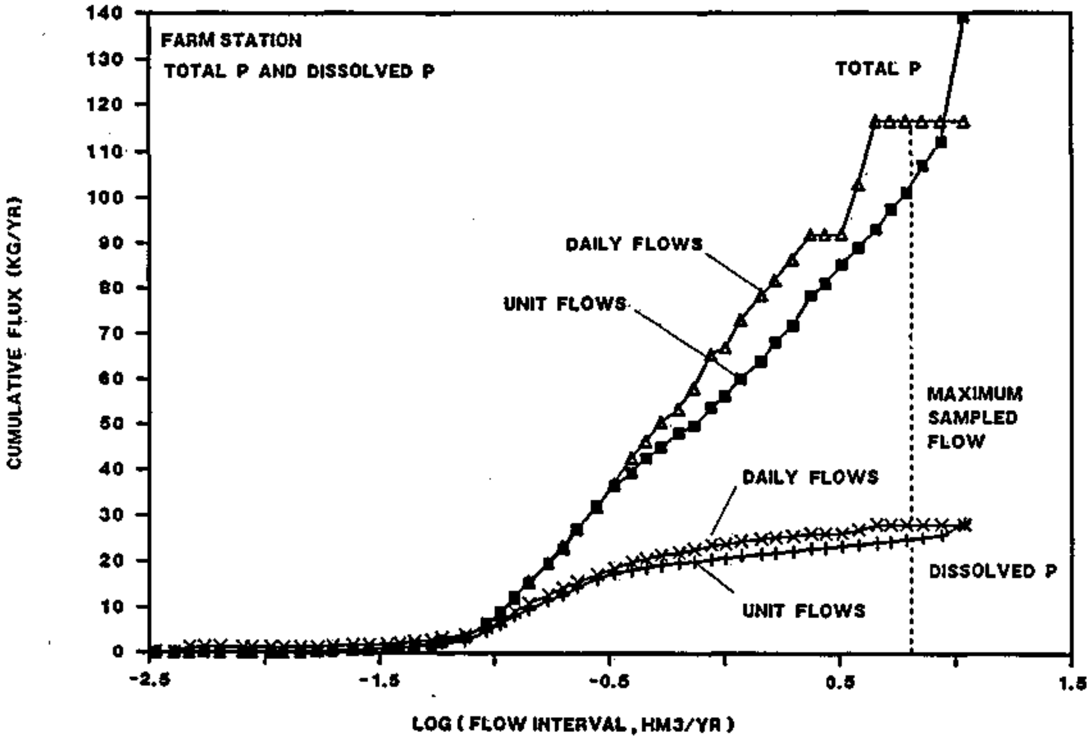
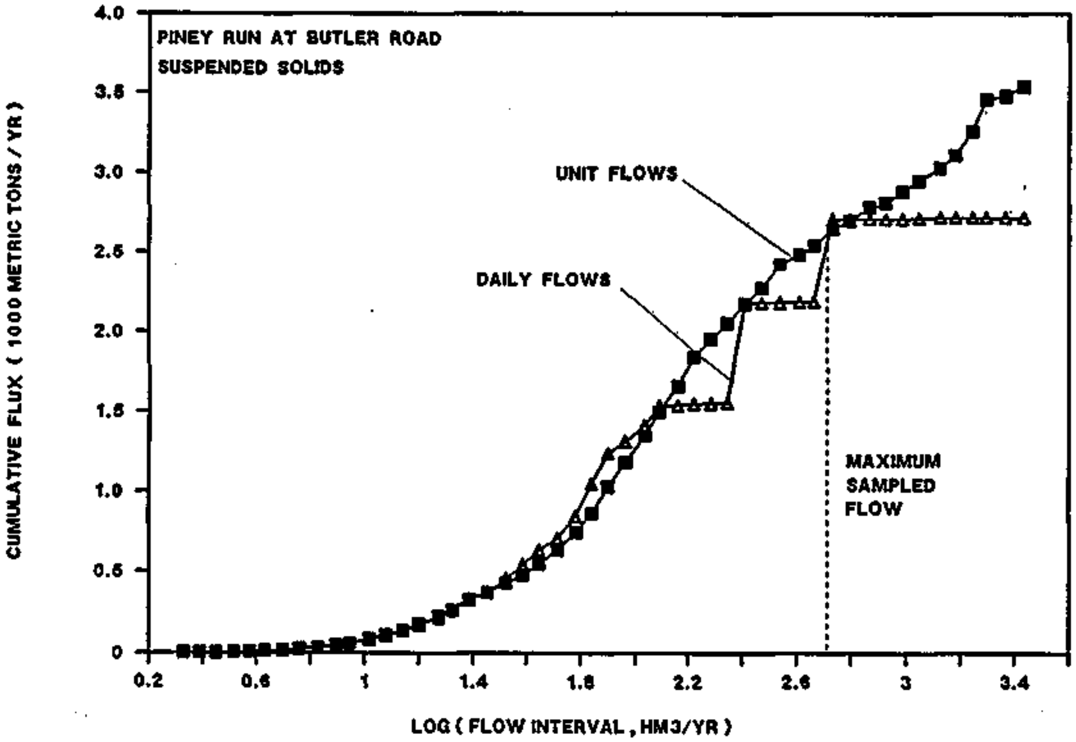
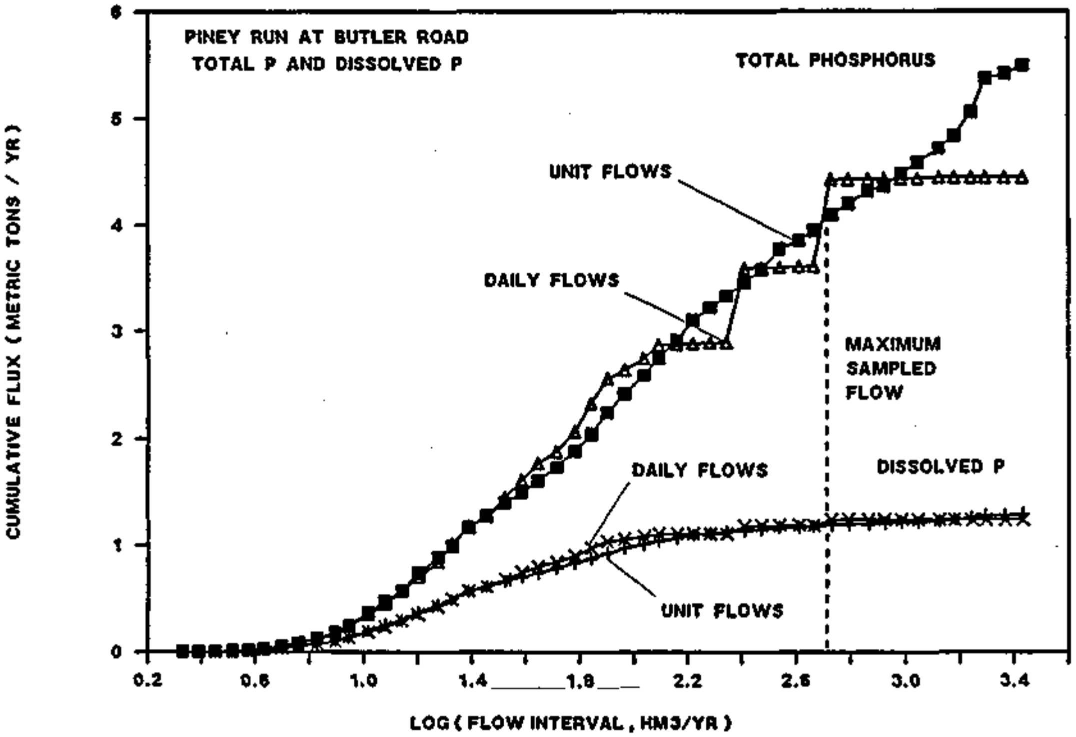


Figure 9
Load Estimate Comparisons - Unit vs. Daily Flows - Piney Run





insensitive to flow averaging interval because of the relatively weak flow/concentration relationship.

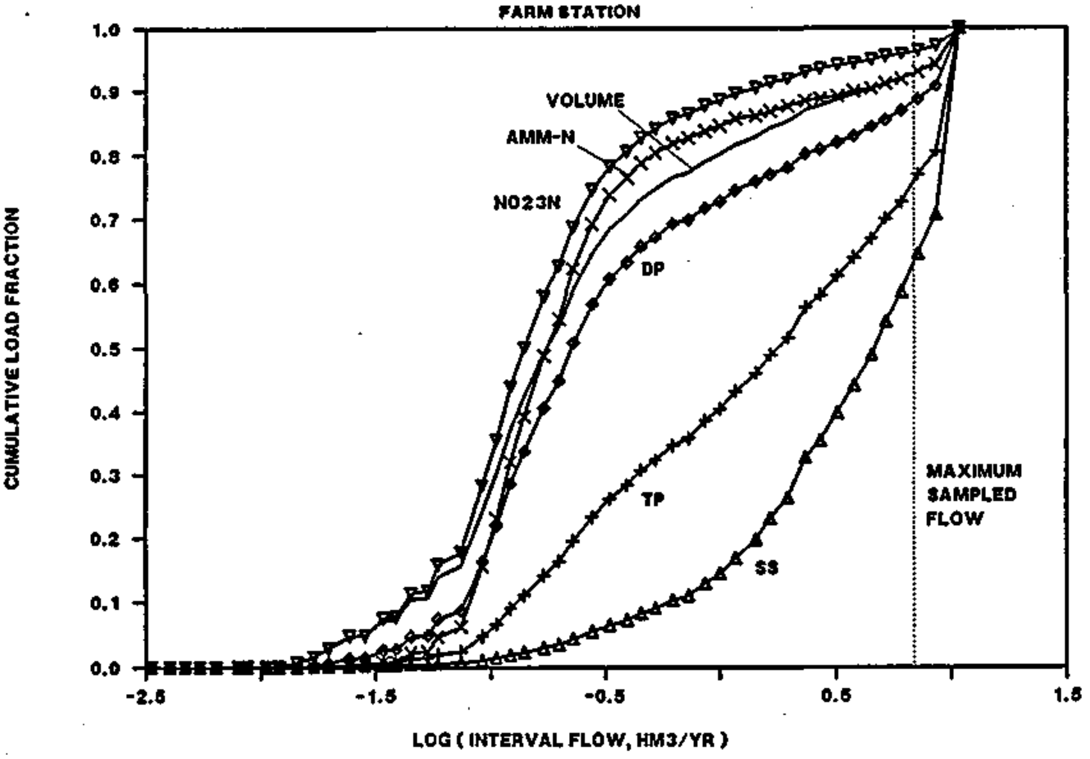
Figure 10 shows cumulative volume and load distributions vs. flow interval for each station and component. These have been developed by mapping log(c) vs. log(q) polynomials onto the unit flow frequency distribution at each station. Dissolved species (ammonia, nitrate, dissolved phosphorus) generally track the volume curves; this reflects relatively weak flow/concentration relationships. Curves for total phosphorus and suspended solids are below those for the other components; this reflects strong flow/concentration relationships and preferential transport of particulate species under high-flow conditions.

2.5 Load Contrasts

Of interest is the extent to which statistically significant changes in longterm average loading can be identified at each station over the period of monitoring resulting from implementation of Best Management Practices in the watersheds. "Longterm average loading" is defined as the flow/concentration relationship mapped onto the frequency distribution of unit flow values for the entire period of record. The **FLUX** "Calculate Contrast Restrict" procedure permits comparison of longterm load estimates developed for a given station and component using sample data from two different time periods. Parametric (t) and nonparametric (Mann-Whitney U) tests are applied to assess statistical significance. Output from this procedure is explained Table 5. Total phosphorus load contrasts calculated using unit and daily flow frequency distributions are listed in Table 6 (Farm Station) and Table 7 (Piney Run at Butler Road). Table 8 summarizes average loads calculated for each station, component, and time period.

As reflected in Figures 8 and 9, calculation of the total load requires estimation of concentration in each flow interval. This can pose problems at extremely high flows which exceed those sampled. Extrapolating the flow/concentration regression outside the range of sampled flows can give highly variable results, particularly since the

Figure 10
Cumulative Load Fractions vs. Flow Interval



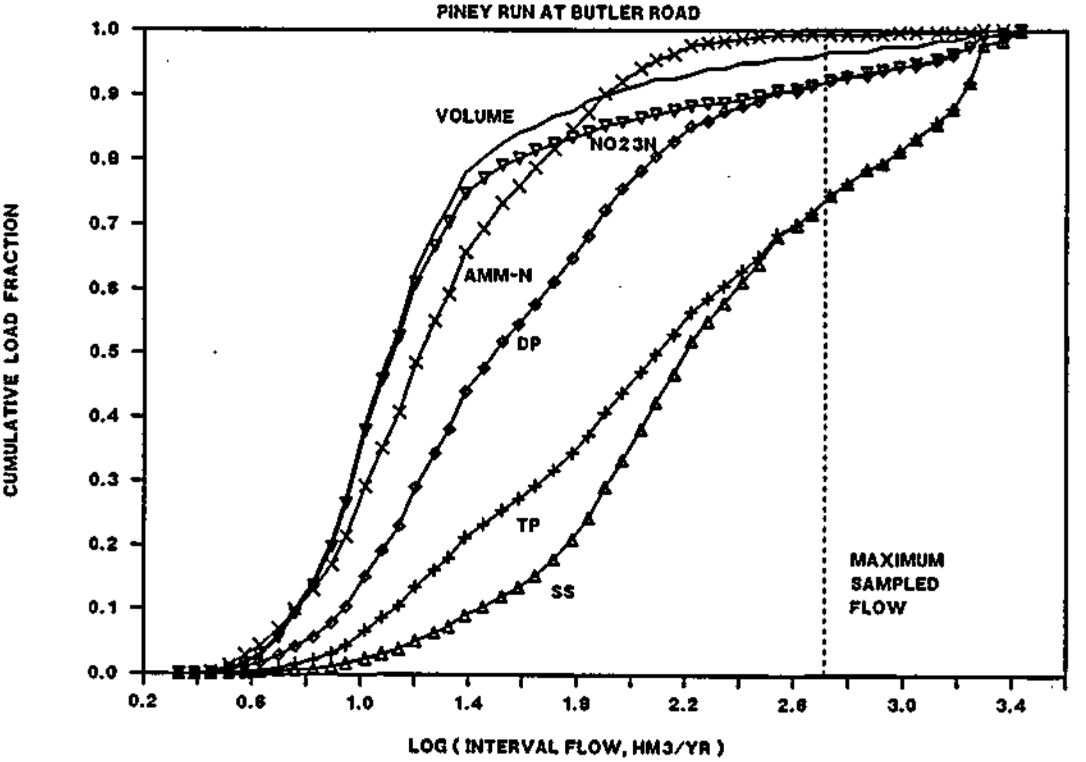


Table 5
Output from FLUX "Calculate Contrast" Procedure

FLUX PROCEDURE = [C C R], Notes are shown in bold print.
Event Duration = 2 days, Calculation Method = 6 (Log/Log Regression)
Flow Strata Upper Bounds = .3 and 99999 hm3/yr
User specifies contrast date of 861201

FLUX calculates sampled flow range during each time period. Define Qmin to Qmax as sampled flow range which is covered during each period (in this case Qmin=.025 and Qmax=6.948 hm3/yr). In applying the C/Q regression model to estimate concentration at a given flow, Q is restricted to this range. The entire flow volume is considered in calculating flux, however.

FLUX calculates loads in each stratum using samples taken before 861201:

```
Farm Station                      VAR=TP              METHOD= 6 REG-3
calculations using sample dates < 861201
sampled flow range =       .014 to      6.948 hm3/yr
model applic range =       .025 to      6.948 hm3/yr
results for period 1:
st  ne freq%        flow        flux       flowc        fluxc       conc    cv autoc
 1  40  95.5         .08        36.8         .07         35.2      477.9  .105  .058
 2  11   4.5         .90      2584.2         .04        115.9     2856.5  .073 -.366
***  51 100.0        .11       151.1         .11        151.1     1322.8  .061  .000
```

st = flow stratum, * = all**
ne = number of sampled events in period
freq% = temporal frequency (percent of unit flow values in stratum)
flow = mean flow rate in stratum (hm3/yr)
flux = mean flux rate in stratum (kg/yr)
flowc = portion of total flow in stratum = flow x freq%/100 (hm3/yr)
fluxc = portion of total flux in stratum = flux x freq%/100 (kg/yr)
conc = flow-weighted concentration in stratum = flux/flow (ppb)
cv = coefficient of variation of mean flux and conc estimates
autoc = autocorrelation coefficient of event pseudo loads (test for serial dependence)

FLUX calculates loads in each stratum using samples taken after 861201:

```
calculations using sample dates >= 861201
sampled flow range =       .025 to     10.967 hm3/yr
model applic range =       .025 to      6.948 hm3/yr
results for period 2:
st  ne freq%        flow        flux       flowc        fluxc       conc    cv autoc
 1  12  95.5         .08        13.8         .07         13.2      179.5  .258  .089
 2  11   4.5         .90      2181.3         .04         97.8     2411.1  .238 -.483
***  23 100.0        .11       111.0         .11        111.0      972.2  .212  .000
```

FLUX calculates decrease in load between two time periods in each stratum and overall:

```
Farm Station                      VAR=TP              METHOD= 6 REG-3
load contrast, critical date >=  861201
decreases: period 1 - period 2

st events          flux        fluxc  std error       t   p(>t) %reduc   %se      mdr%
 1     52          23.0         22.0        5.0    4.40   .000   62.4  10.5      33.7
 2     22         402.9         18.1       24.6     .73   .240   15.6  21.0      31.0
***    74          40.0         40.0       25.3    1.58   .057   26.5  16.2      27.5
```

events = total number of sampled events in both periods
flux = period$_1$ flux - period$_2$ flux (kg/yr)
fluxc = period$_1$ fluxc - period$_2$ fluxc (kg/yr)
std error = standard error of decrease in flux (kg/yr)
t = approx. t statistic for testing significance of difference in load
p(>t) = significance level of t-statistic (one-tailed)
%reduc = percent reduction in load between two time periods = 100% x (F_1 - F_2)/F_1
%se = standard error of %reduc
mdr% = minimum detectable % reduction in load, given event counts and coefficients of variation (CV) in each
stratum, assuming that CV's are independent of flux magnitude; ~ %reduc at p(>t)=.05

```
Mann-Whitney Test on Event Pseudo-Values:
Period 1   N =  51, Median =      147.62
Period 2   N =  23, Median =      104.43
T =      626.,  prob(>T) =  .003
```

Nonparametric test for difference in distribution of event pseudo-values between two time periods; alternative to parametric t-test applied above.

Table 6
Total P Load Contrasts vs. Flow Averaging Interval - Farm Station

```
LOAD CONTRAST - FARM STATION - USING UNIT FLOW VALUES:

Farm Station                       VAR=TP              METHOD= 6 REG-3
calculations using sample dates < 861201
sampled flow range =          .014 to       6.948 hm3/yr
model applic range =          .025 to       6.948 hm3/yr
results for period 1:
st  ne freq%          flow        flux        flowc        fluxc        conc     cv autoc
 1  40  95.5           .08        36.8          .07         35.2       477.9   .105  .058
 2  11   4.5           .90      2584.2          .04        115.9      2856.5   .073 -.366
***  51 100.0           .11       151.1          .11        151.1      1322.8   .061  .000

calculations using sample dates >= 861201
sampled flow range =          .025 to      10.967 hm3/yr
model applic range =          .025 to       6.948 hm3/yr
results for period 2:
st  ne freq%          flow        flux        flowc        fluxc        conc     cv autoc
 1  12  95.5           .08        13.8          .07         13.2       179.5   .258  .089
 2  11   4.5           .90      2181.3          .04         97.8      2411.1   .238 -.483
***  23 100.0           .11       111.0          .11        111.0       972.2   .212  .000

load contrast, critical date >=  861201
decreases: period 1 - period 2

st events          flux        fluxc  std error         t   p(>t) %reduc  %se      mdr%
 1      52         23.0         22.0        5.0      4.40   .000   62.4  10.5      33.7
 2      22        402.9         18.1       24.8      0.73   .240   15.6  21.0      31.0
***     74         40.0         40.0       25.3      1.58   .057   26.5  16.2      27.5

Mann-Whitney Test on Event Pseudo-Values:
Period 1   N =  51, Median =       147.62
Period 2   N =  23, Median =       104.43
T =       626.,  prob(>T) =  .003


LOAD CONTRAST - FARM STATION - USING DAILY FLOW VALUES:

Farm Station Daily Flows           VAR=TP              METHOD= 6 REG-3
calculations using sample dates < 861201
sampled flow range =          .014 to       6.948 hm3/yr
model applic range =          .025 to       6.948 hm3/yr
results for period 1:
st  ne freq%          flow        flux        flowc        fluxc        conc     cv autoc
 1  40  93.9           .08        37.4          .07         35.2       477.6   .104  .058
 2  11   6.1           .67      1498.7          .04         91.0      2223.1   .106 -.089
***  51 100.0           .11       126.2          .11        126.2      1101.2   .081  .000

calculations using sample dates >= 861201
sampled flow range =          .025 to      10.967 hm3/yr
model applic range =          .025 to       6.948 hm3/yr
results for period 2:
st  ne freq%          flow        flux        flowc        fluxc        conc     cv autoc
 1  12  93.9           .08        14.1          .07         13.2       179.4   .258  .088
 2  11   6.1           .67      1203.2          .04         73.1      1784.8   .218 -.255
***  23 100.0           .11        86.3          .11         86.3       752.9   .189  .000

Farm Station Daily Flows           VAR=TP              METHOD= 6 REG-3
load contrast, critical date >=  861201
decreases: period 1 - period 2

st events        flux        fluxc  std error        t   p(>t)%reduc   %se     mdr%
 1      52       23.4         22.0        5.0     4.40   .000   62.4  10.5     33.6
 2      22      295.5         17.9       18.6     0.96   .174   19.7  19.5     31.6
***     74       39.9         39.9       19.3     2.07   .020   31.6  14.1     26.8

Mann-Whitney Test on Event Pseudo-Values:
Period 1   N =  51, Median =       120.99
Period 2   N =  23, Median =        78.68
T =       614.,  prob(>T) =  .002
```

Table 7
Total P Load Contrasts vs. Flow Averaging Interval - Piney Run

```
LOAD CONTRAST - PINEY RUN - USING UNIT FLOW VALUES:

Piney Run                          VAR=TP              METHOD= 6 REG-3
calculations using sample dates < 840901
sampled flow range =        3.921 to     508.003 hm3/yr
model applic range =        3.921 to     508.003 hm3/yr
results for period 1:
st  ne freq%          flow        flux        flowc        fluxc        conc     cv autoc
 1  17  52.9          6.31       423.0         3.33        223.6        67.1  .134  .032
 2  27  45.7         15.31      3635.9         7.00       1662.6       237.5  .116  .396
 3  10   1.4        128.14    418422.2         1.81       5911.5      3265.4  .128 -.352
***  54 100.0         12.14      7797.7        12.14       7797.7       642.2  .100  .000

calculations using sample dates >= 840901
sampled flow range =        3.555 to    2027.367 hm3/yr
model applic range =        3.921 to     508.003 hm3/yr
results for period 2:
st  ne freq%          flow        flux        flowc        fluxc        conc     cv autoc
 1  14  52.9          6.31       453.4         3.33        239.6        71.9  .169 -.292
 2  23  45.7         15.31      2827.9         7.00       1293.2       184.8  .242 -.061
 3  14   1.4        128.14    252326.5         1.81       3564.9      1969.2  .177 -.241
***  51 100.0         12.14      5097.7        12.14       5097.7       419.8  .138  .000

Piney Run                          VAR=TP              METHOD= 6 REG-3
load contrast, critical date >=  840901
decreases: period 1 - period 2

st events        flux        fluxc  std error        t    p(>t)%reduc    %se      mdr%
 1      31       -30.3       -16.0       50.4    -.32    .376   -7.2  23.1      30.4
 2      50       807.9       369.5      367.8    1.00    .161   22.2  20.9      33.3
 3      24    166095.7      2346.6      985.8    2.38    .012   39.7  13.2      30.5
***     105      2700.0      2700.0     1053.3    2.56    .006   34.6  11.2      24.1

Mann-Whitney Test on Event Pseudo-Values:
Period 1   N =  54, Median =     7611.54
Period 2   N =  51, Median =     4870.74
T =      1886.,  prob(>T) =  .000

LOAD CONTRAST - PINEY RUN - USING DAILY FLOW VALUES:

Piney Daily Values                 VAR=TP              METHOD= 6 REG-3
calculations using sample dates < 840901
sampled flow range =        3.921 to     508.003 hm3/yr
model applic range =        3.921 to     508.003 hm3/yr
results for period 1:
st  ne freq%          flow        flux        flowc        fluxc        conc     cv autoc
 1  17  55.9          6.67       451.3         3.73        252.5        67.6  .133  .032
 2  27  42.7         16.76      4456.8         7.15       1902.6       266.0  .113  .427
 3  10   1.4        106.28    289695.6         1.46       3970.4      2725.8  .126 -.486
***  54 100.0         12.34      6125.6        12.34       6125.6       496.3  .089  .000

calculations using sample dates >= 840901
sampled flow range =        3.555 to    2027.367 hm3/yr
model applic range =        3.921 to     508.003 hm3/yr
results for period 2:
st  ne freq%          flow        flux        flowc        fluxc        conc     cv autoc
 1  14  55.9          6.67       472.8         3.73        264.5        70.9  .171 -.292
 2  23  42.7         16.76      3932.9         7.15       1678.9       234.7  .290 -.053
 3  14   1.4        106.28    180867.4         1.46       2478.9      1701.8  .143 -.128
***  51 100.0         12.34      4422.3        12.34       4422.3       358.3  .137  .000

Piney Daily Values                 VAR=TP              METHOD= 6 REG-3
load contrast, critical date >=  840901
decreases: period 1 - period 2

st events        flux        fluxc  std error        t    p(>t)%reduc    %se      mdr%
 1      31       -21.5       -12.0       56.5    -.21    .414   -4.8  22.8      30.4
 2      50       524.0       223.7      532.5    0.42    .340   11.8  27.5      36.3
 3      24    108828.2      1491.6      613.9    2.43    .011   37.6  11.9      28.0
***     105      1703.2      1703.2      814.6    2.09    .018   27.8  11.8      22.9

Mann-Whitney Test on Event Pseudo-Values:
Period 1   N =  54, Median =     5907.13
Period 2   N =  51, Median =     4091.99
T =      2001.,  prob(>T) =  .000
```

Table 8
Longterm Average Flux Estimates vs. Station, Component, and Time Period

VARIABL	PD	EVENTS	FLOW HM3/YR	FLUX KG/YR	CV	CONC PPB	FLUX REDUCTION (KG/YR)			MDR%	SIGNIF. LEVELS	
							MEAN	STD. ERR	%		T-TEST	MANN-WHITNEY
YOHN'S FARM STATION, DIVIDING DATE = 861201												
tp	1	51	0.114	151	0.061	1325						
tp	2	23	0.114	111	0.212	974	40	25	26.5%	27.5%	0.057	0.003
dp	1	29	0.114	53	0.500	461						
dp	2	21	0.114	16	0.169	143	36	26	69.0%	83.9%	0.086	0.001
ss	1	32	0.114	97155	0.189	852237						
ss	2	26	0.114	39076	0.273	342772	58079	21236	59.8%	41.4%	0.004	0.001
amm	1	28	0.114	356	0.193	3126						
amm	2	23	0.114	147	0.412	1291	209	92	58.7%	48.2%	0.013	0.001
no23n	1	24	0.114	521	0.079	4571						
no23n	2	23	0.114	729	0.065	6396	-208	63	-39.9%	16.1%	0.001	0.001
inorgn	1	24	0.114	878	0.091	7697						
inorgn	2	23	0.114	876	0.088	7687	1	111	0.1%		n.s.	
PINEY RUN AT BUTLER ROAD, DIVIDING DATE = 840901												
tp	1	54	12.143	7798	0.100	642						
tp	2	51	12.143	5098	0.138	420	2700	1050	34.6%	24.1%	0.006	0.001
dp	1	35	12.143	1631	0.105	134						
dp	2	41	12.143	999	0.216	82	632	275	38.7%	30.5%	0.012	0.001
ss	1	46	12.143	8602793	0.109	708457						
ss	2	55	12.143	2433188	0.309	200378	6169605	1201905	71.7%	37.0%	0.001	0.001
amm	1	41	12.143	5002	0.151	412						
amm	2	43	12.143	1917	0.177	158	3085	828	61.7%	32.1%	0.001	0.001
no23n	1	42	12.143	34752	0.094	2862						
no23n	2	41	12.143	44724	0.044	3683	-9972	3814	-28.7%	16.8%	0.005	0.001
inorgn	1	41	12.143	39754	0.084	3274						
inorgn	2	41	12.143	46641	0.043	3841	-6887	3902	-17.3%		0.05	

Table 8 (ct).
Longterm Average Flux Estimates vs. Station, Component, and Time Period

VAR.	PD	EVENTS	FLOW HM3/YR	FLUX KG/YR	CV	CONC PPB	FLUX REDUCTION (KG/YR) MEAN	STD. ERR	%	T-TEST	SIGNIF.
HAMPSTEAD STP, DIVIDING DATES = 840801 & 860101											
tp	1	68	0.30	747	0.119	2490					
tp	2	31	0.34	404	0.116	1188					
tp	3	40	0.33	284	0.098	861	463	93	62.0%	4.97	< .01
dp	1	28	0.29	470	0.083	1621					
dp	2	16	0.30	207	0.225	690					
dp	3	23	0.31	150	0.130	484	320	44	68.1%	7.34	< .01
ss	1	57	0.30	5214	0.262	17380					
ss	2	24	0.34	3376	0.223	9929					
ss	3	43	0.34	4131	0.138	12150	1083	1480	20.8%	0.73	0.23
amm	1	59	0.30	6551	0.052	21837					
amm	2	25	0.34	3627	0.126	10668					
amm	3	39	0.34	65	0.196	191	6486	341	99.0%	19.03	< .01
no23n	1	57	0.30	378	0.279	1260					
no23n	2	23	0.33	1845	0.092	5591					
no23n	3	35	0.34	10088	0.072	29671	-9710	734	-2568.8%	-13.23	< .01
inorgn	1	57	0.30	6929	0.051	23097					
inorgn	2	23	0.33	5472	0.089	16582					
inorgn	3	35	0.34	10153	0.072	29862	-3224	809	-46.5%	-3.98	< .01
PINEY RUN AT BUTLER ROAD NONPOINT = PINEY RUN - HAMPSTEAD STP, DIVIDING DATE = 840901											
tp	1	54	11.843	7051	0.111	595					
tp	2	51	11.813	4814	0.146	408	2237	1054	31.7%	2.12	< .01
dp	1	35	11.853	1161	0.151	98					
dp	2	41	11.833	849	0.255	72	312	279	26.9%	1.12	0.13
ss	1	46	11.843	8597579	0.109	725963					
ss	2	55	11.803	2429057	0.310	205800	6168522	1201906	71.7%	5.13	< .01
amm	1	41	11.843	-1549	-0.535	-131					
amm	2	43	11.803	1852	0.183	157	-3401	895	219.6%	-3.80	< .01
no23n	1	42	11.843	34374	0.095	2902					
no23n	2	41	11.803	34636	0.061	2935	-262	3884	-0.8%	-0.07	n.s.
inorgn	1	41	11.843	32825	0.103	2772					
inorgn	2	41	11.803	36488	0.058	3091	-3663	3986	-11.2%	-0.92	0.18

regression slopes may vary with flow range (Figures 3 and 5). This problem is addressed by restricting the flow range to the maximum flow which was sampled during both time periods (Q_{max}) for the purpose of estimating concentration:

For $Q > Q_{max}$, CONC = $F(Q_{max})$, FLUX = Q x CONC

Q_{max} = MINIMUM [Q_{max}(Period 1), Q_{max}(Period 1)]

F = log(CONC) vs. log(Q) regression model

A similar procedure is used for minimum flows, although these have little influence on the total load calculations. Because of the sensitivity of load calculations to sampled concentrations in the high flow stratum, restricting the flow range in the above manner is desirable for developing valid load contrasts; otherwise, the analysis must rely upon extrapolation of flow/concentration relationship into unsampled flow ranges which may have strong influence on the results.

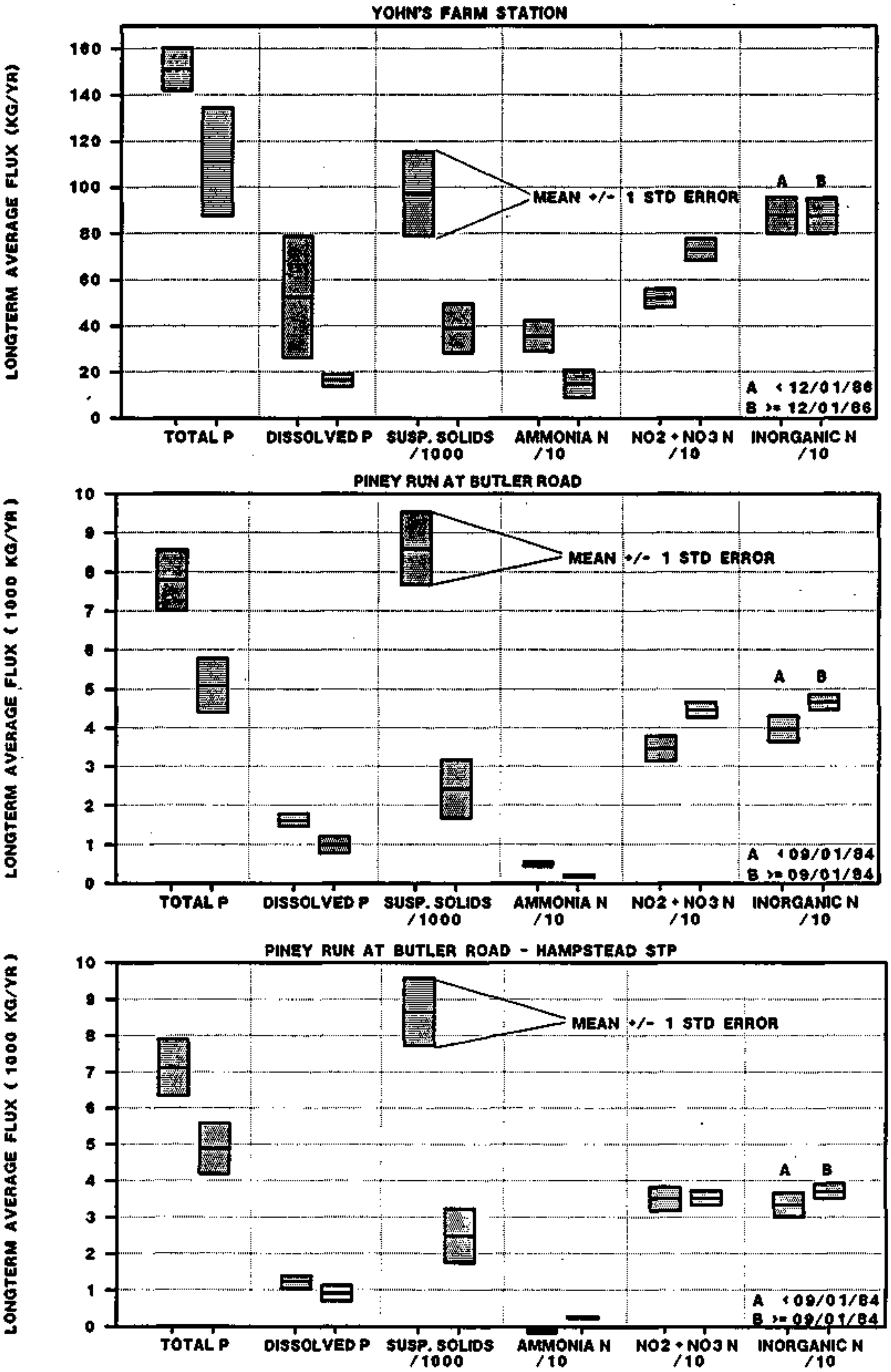
The precision of an average load estimate for a given station, component, and time period is represented by the coefficient of variation (CV). This is estimated using the jackknife procedure, as described in the **FLUX** documentation (Walker,1987,1988). This procedure assumes that the values being jackknifed (in this case, samples) are statistically independent. Error CV's are underestimated when there is significant serial correlation in the samples, which tends to be the case when the data set includes discrete samples within storm events. To reduce this problem, **FLUX** Version 4.2 permits jackknifing of "events". An "event" is defined as a group of samples within the same flow stratum which are collected within L days of one another. An L value of 2 days has been used in developing the load estimates in Tables 5-8. This approach has been found to reduce the serial correlation of jackknifed loads to negligible levels in most cases and thus to improve the reliability of the error CV estimates.

FLUX Model 6 (log(c) vs. log(q) regression) has been applied to the stream station data, stratified into 2 or 3 flow ranges. In the absence of flow data for unsampled dates, FLUX Model 1 (average load) has been used to estimate loads from Hampstead WWTP for each of three time periods. Estimates of nonpoint loads for Piney Run (Table 8) have been developed by subtracting the Hampstead WWTP loads from the Butler Road loads during each time period. This assumes that the component behaves conservatively between the point-source discharge and the mouth of the watershed. Instream nitrification of the Hampstead ammonia load likely accounts for negative nonpoint loadings computed for ammonia. Inorganic nitrogen loads have been estimated for all stations by adding the respective ammonia and nitrate+nitrite nitrogen loads (along with their respective variances). Lack of organic nitrogen data precludes evaluation of total nitrogen loads.

Confidence ranges for longterm stream loads during each time period are shown in Figure 11. As indicated in Table 8, statistically significant differences ($p < .05$, one-tailed) between time periods are indicated in 19 out of 24 cases, based upon t-tests and/or Mann-Whitney U tests. The latter tests yield consistently lower probability levels, which may reflect the greater power of the nonparametric procedure for detecting changes in the jackknifed load distributions (Lettenmaier, 1976).

Estimated percentage reductions in total phosphorus loadings are 27% for the Farm Station, 35% for Piney Run, and 32% for Piney Run adjusted for the Hampstead WWTP load. Corresponding percentage reductions in dissolved phosphorus (of greater significance to Loch Raven Reservoir than total phosphorus) are 69%, 39%, and 27%, respectively. Reductions in suspended solids loadings are 60%, 72%, and 72%, respectively. Results are consistent with the hypothesis that watershed management activities had measurable effects on nutrient and sediment loadings which are of importance with respect to management of eutrophication and sedimentation in downstream Loch Raven Reservoir.

Figure 11
Flux Estimates vs. Time Period and Component



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Reductions in ammonia nitrogen loadings are balanced by increases in nitrate+nitrite nitrogen at the Farm station. This is consistent with the hypothesis that nitrogen in animal waste reached the stream in a relatively short time scale before installation of the manure storage facilities, whereas it reached the stream in nitrified form after installation of the storage facility. Nitrification may occur during waste storage and subsequent application to fields. Inorganic nitrogen was also balanced at the Piney Run station, with adjustment for Hampstead WWTP loads.

The estimates of longterm average loads and changes therein assume that errors in the stream concentration vs. flow relationship are independent and random. Weak seasonal dependencies have been observed in some cases, but these are not strong enough to justify consideration in annual load calculations. The calculation model assumes that concentration depends upon flow and is independent of flow history. At a given flow level, particulate concentrations on the rising portion of the storm hydrograph (or seasonal hydrograph) often tend to be higher than those on the falling portion of the hydrograph. The load calculations assume that the stream data sets include both rising and falling flows in a proportion which is representative of the entire flow record. Modification of load calculation procedures to account for such phenomena is a possible topic for future research.

2.6 Detection of Load Changes

Table 9 derives equations used by the **FLUX** "Calculate Contrast" procedures to calculate "**MDR%**", the minimum percentage reduction in longterm average load which can be detected for a given monitoring station, component, and sampling intensity. The concept of **MDR%** is described by Spooner et al (1987) with respect to the detection of step changes or trends in stream water quality. In this case, "detection" is defined by rejection of the null hypothesis that the long term load has not changed, using a t-test ($p < .05$, one-tailed) applied to the populations of event pseudo-values (Mosteller and Tukey, 1978; Walker, 1988) from different time periods. The derivation of **MDR%** assumes that

Table 9
Calculation of Minimum Detectable Percent Decrease in Load between Two Time Periods

Symbols	Period 1	Period 2
Mean Load	m_1	m_2
CV(Mean)	c_1	c_2
Events	n_1	n_2

Variance of Load Reduction (m_1 and m_2 are independent):

$$\mathrm{Var}(m_1 - m_2) = \mathrm{Var}(m_1) + \mathrm{Var}(m_2) = (m_1 c_1)^2 + (m_2 c_2)^2$$

t-Test for Null Hypothesis: $m_1 = m_2$

$$t = \frac{(m_1 - m_2)}{[\ (m_1 c_1)^2 + (m_2 c_2)^2\ ]^{1/2}} \tag{1}$$

t = one-tailed t-statistic with $n_1 + n_2 - 2$ degrees of freedom
$\sim$ 1.7 for dof > 20 and significance level of .05

In Terms of Load Ratio $r = m_2/m_1$:

$$1 - r = (m_1 - m_2)/m_1 = t\ [\ c_1^2 + c_2^2\ r^2\ ]^{1/2} \tag{2}$$

Solution for MDR% = Minimum Detectable Reduction (%):

$$\mathrm{MDR\%} = 100\ (\ 1 - r\ ) \tag{3}$$

$$= 100\ \frac{t^2 c_2^2 - [\ 1 - (1 - t^2 c_2^2)(1 - t^2 c_1^2)\ ]^{1/2}}{t^2 c_2^2 - 1} \tag{4}$$

$$\sim 100\ [\ 1 - \exp(-\ t\ [\ c_1^2 + c_2^2\ ]^{1/2}\ )\ ] \tag{5}$$

For Balanced Design: $c_1 \sim c_2 \sim c\ ;\ \ n_1 \sim n_2 \sim n$

$$\mathrm{MDR\%} = 100\ \frac{t^2 c^2 - [\ 2 t^2 c^2 - t^4 c^4\ ]^{1/2}}{t^2 c^2 - 1} \tag{6}$$

$$\sim\ 100\ [\ 1 - \exp(-\ t\ c\ 2^{1/2})\ ] \tag{7}$$

Sensitivity to Alternative Sampling Frequency n':

$$c'^2 \sim c^2\ n\ /\ n' = y^2\ /\ n'\ ,\quad y = c\ n^{1/2} \tag{8}$$

the load coefficient of variation (c in Table 9) depends upon the station, component, and number of sampled events, but is independent of mean load. This is consistent with the generally lognormal characteristics of stream flow and concentration data.

The equations in Table 9 are applied to load estimates for each station and component in Table 10. **MDR%** values range from 15% to 59% for these data sets. For total phosphorus, **MDR%** values of 28% and 24% are calculated, based upon data from the Farm and Piney Run stations, respectively.

Figure 12 plots a generalized relationship between **MDR%** and number of sampled events, based upon equations (6) and (8) in Table 9. Curves are shown for various values of the parameter "y" ($= c\ n^{1/2}$), as tabulated in Table 10 for each station and component. This parameter represents variability in the stream flow/concentration relationship, as reflected, for example, by the standard error of estimate for a log concentration vs. log flow regression. As indicated in Table 10, y values are relatively high (.97-2.0) for ammonia and relatively low (.28-.62) for nitrate+nitrite nitrogen. The range for total phosphorus (as reflected by the shaded area in Figure 10) is .4 to 1.0.

With prior estimates of y derived from historical monitoring data, Figure 12 can be used to estimate the minimum detectable percent reduction in longterm average stream loading for a given number of events (n) sampled before and after the hypothetical change. Figure 12 generally indicates that changes in total phosphorus loading on the order of 50% or more are detectable for a modest number of sampled events per time period (~10), whereas detection of a 20% change would require more than 60 events. Note that an "event", as defined here, is any 2-day period. Results apply to the mixes of baseflow and storm-event samples which are typical of the Farm and Piney Run stations.

The **FLUX** "Utilities List Breakdown" procedure provides guidelines for optimizing sample allocation among flow strata for the purpose of calculating loads. Phosphorus load breakdowns for each station are listed

Table 10

Calculation of Minimum Detectable Percent Reductions in Load for Each Station and Variable

Variable	n_1	n_2	c_1	c_2	y_1	y_2	n_m	...PERCENT DECREASE----		
								MDR%	APPROX.	OBSERVED
Yohn's Farm										
tp	51	23	0.061	0.212	0.436	1.017	37	27.5%	30.8%	26.5%
dp	29	21	0.500	0.169	2.693	0.774	25	84.0%	58.7%	69.0%
ss	32	26	0.189	0.273	1.069	1.392	29	41.4%	42.6%	59.8%
amm	28	23	0.193	0.412	1.021	1.976	26	48.2%	53.4%	58.7%
no23n	24	23	0.079	0.065	0.387	0.312	24	16.1%	15.8%	-39.9%
Piney Run at Butler Road										
tp	54	51	0.100	0.138	0.735	0.986	53	24.0%	24.6%	34.6%
dp	35	41	0.105	0.216	0.621	1.383	38	30.5%	33.0%	38.7%
ss	46	55	0.109	0.309	0.739	2.292	51	37.0%	42.0%	71.7%
amm	41	43	0.151	0.177	0.967	1.161	42	32.1%	32.1%	61.7%
no23n	42	41	0.095	0.044	0.616	0.282	42	16.9%	16.0%	-28.7%

n_1,n_2 = number of events for periods 1 and 2

c_1,c_2 = coefficients of variation for mean flux estimates

y1,y2 = load cv's, $y_1 = c_1\, n_1^{1/2}$, $y_2 = c_2\, n_2^{1/2}$

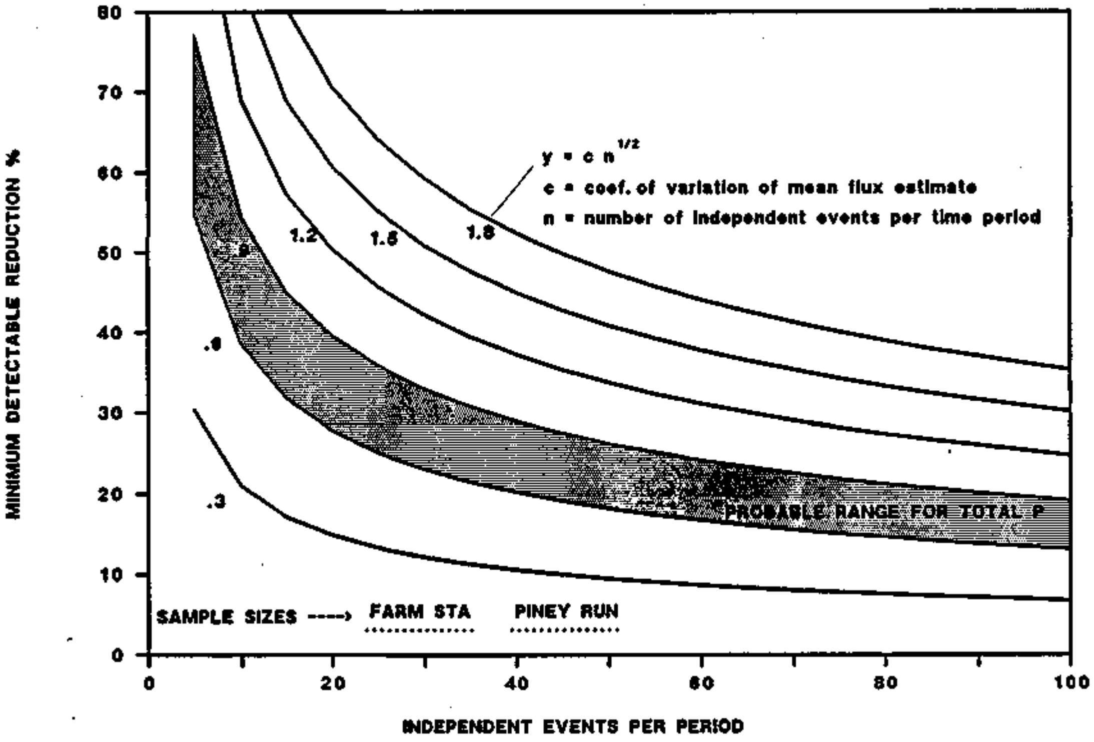
n_m = average number of events per period

MDR% = minimum detectable percent reduction (Eq. 4 in Table 9)

APPROX. = approximate formula for MDR% (Eq. 5 in Table 9)

OBSERVED = observed percent reduction in load

Figure 12
Minimum Detectable Reduction vs. Load CV and Sample Size



in Table 11. Two flow strata have been used for calculating loads at the Farm Station (cutpoint = .3 hm^3/yr). The lower stratum accounted for 70.3% of the sampled events (ne%), 20.8% of the flux (flux%), and 4.6% of the flux variance (var%). For the optimal sample allocation (opt%), the lower stratum would include only 25.3% of the events. Shifting to the optimal sample allocation would reduce the coefficient of variation of the total load estimate (cv) from .116 to .083 for the same total number of events. This would have the effect of reducing the "y" value used in calculating the MDR% by 29% and reducing the MDR% accordingly. For Piney Run, three flow strata have been used (cutpoints = 10 and 50 hm^3/yr). Shifting from the historical event distribution (29.5%, 47.6%, 22.9%) to the optimal distribution (1.8%, 15.1%, 83.1%) would reduce the load cv from .193 to .110 or 43%.

The feasibility of actually sampling the stream according to the theoretically optimal allocation is limited. For example, to place the desired 83.1% of 105 events in the third flow stratum at Piney Run, 87 high-flow events would have to be sampled over the same time period (in this case, ~5.3 years). As indicated in Table 11, this stratum has a temporal frequency (freq%) of only 1.4%. Based upon the 2-day-long event duration, only 82 separate events (periods with flows > 50 hm^3/yr) occurred during the entire 5.3-year period of record. Thus, it would be impossible to achieve the optimal allocation of 87 high-flow events. The load breakdowns generally indicate, however, that the precision of loading estimates would improve with a greater relative emphasis on high-flow conditions. To provide the greatest resolution of the flow/concentration relationship, compositing over wide ranges of flow should be avoided in favor of discrete samples or compositing over smaller flow ranges.

3.0 ANALYSIS OF RESERVOIR MONITORING DATA

This section analyzes phosphorus and related water quality data collected in Loch Raven Reservoir between 1982 and 1987. Spatial and temporal variance components are quantified and used to estimate the precision of annual and longterm summary statistics derived from the

Table 11
Total Phosphorus Loads by Flow Strata - All Sample Dates Combined

Farm Station VAR=TP METHOD= 6 REG-3

st	ne	freq%	flow	flux	flowc	fluxc	conc	cv	autoc
1	52	95.5	.08	31.2	.07	29.8	404.2	.120	.396
2	22	4.5	.90	2533.6	.04	113.6	2800.5	.143	-.189
***	74	100.0	.11	143.4	.11	143.4	1255.4	.116	.000

sample allocation:

st	nc	ne	ne%	opt%	freq%	vol%	flux%	var%	variance-c	cv
1	56	52	70.3	25.3	95.5	64.5	20.8	4.6	.1281E+02	.120
2	117	22	29.7	74.7	4.5	35.5	79.2	95.4	.2653E+03	.143
***	173	74	100.0	100.0	100.0	100.0	100.0	100.0	.2781E+03	.116
opt	173	74							.1412E+03	.083

Piney Run VAR=TP METHOD= 6 REG-3

st	ne	freq%	flow	flux	flowc	fluxc	conc	cv	autoc
1	31	52.9	6.31	426.9	3.33	225.7	67.7	.115	.016
2	50	45.7	15.31	3270.6	7.00	1495.6	213.7	.115	.337
3	24	1.4	128.14	384686.2	1.81	5434.8	3002.1	.252	-.143
***	105	100.0	12.14	7156.1	12.14	7156.1	589.3	.193	.000

sample allocation:

st	nc	ne	ne%	opt%	freq%	vol%	flux%	var%	variance-c	cv
1	83	31	29.5	1.8	52.9	27.5	3.2	.0	.6692E+03	.115
2	111	50	47.6	15.1	45.7	57.6	20.9	1.6	.2971E+05	.115
3	69	24	22.9	83.1	1.4	14.9	75.9	98.4	.1878E+07	.252
***	263	105	100.0	100.0	100.0	100.0	100.0	100.0	.1908E+07	.193
opt	263	105							.6211E+06	.110

Notes: The above table was generated using the FLUX "Utilities List Breakdown" Procedure

Term Definitions are as follows:

freq% = frequency (% of time)
*** = all strata
flow = mean flow (hm3/yr)
flux = mean flux or load (kg/yr)
flowc = mean flow x freq. (hm3/yr)
fluxc = mean flux x freq. (kg/yr)
conc = flux/flow (ppb)
cv = coefficient of variation
autoc = autocorrelation coefficient of pseudo loads (reflects serial correlation of events within stratum)

nc = number of samples
ne = number of events
ne% = % of total events
opt% = % of events yielding minimum variance in total flux estimate
vol% = % of total flow volume
flux% = % of total flux
var% = % of total flux variance
variance-c = stratum contribution to variance in total flux (kg/yr)^2
opt = estimated variance and cv of mean flux if events were distributed among strata (according to opt%)

monitoring data. The feasibility of detecting changes in the longterm mean phosphorus concentration is evaluated for alternative sampling program designs.

3.1 Data Summaries

The analysis considers total phosphorus, chlorophyll-a, and transparency data collected at five monitoring stations in Loch Raven Reservoir (Figure 13). Although the water intake station (near dam) was also sampled in 1982 and 1983, the analysis focuses on data from the 1984-1987 period, when all of the stations were operating. The near-dam station averaged 19 sampling dates per growing season (April-September) for total phosphorus, 8 dates per season for chlorophyll-a, and 22 dates per season for Secchi depth. The remaining stations were sampled an average of 6 dates per season (~monthly intervals) for each variable. For each date and station, phosphorus and chlorophyll-a samples were generally collected at 10-foot intervals.

Median concentrations have been computed for each station and date for samples in the surface layer (0-30 feet) and subsequently used to compute seasonal mean values. This data summary procedure provides a degree of protection against outliers, since the presence of one errant observation in a given vertical profile containing at least 3 samples will not influence the median value for the corresponding date or the seasonal mean concentration. Table 12 lists the number of observations, mean, and coefficient of variation of the mean for each variable, station, and year. Summary statistics for all four years have been computed by averaging the annual means. Reservoir-mean values have been approximated by averaging the station means for each year (without spatial weighting factors). Figure 14 displays the 67% confidence limits (mean +/- 1 standard error) for each variable, station, and year.

The data summaries provide the following estimates of longterm means as at the intake station:

Figure 13
Loch Raven Sampling Stations

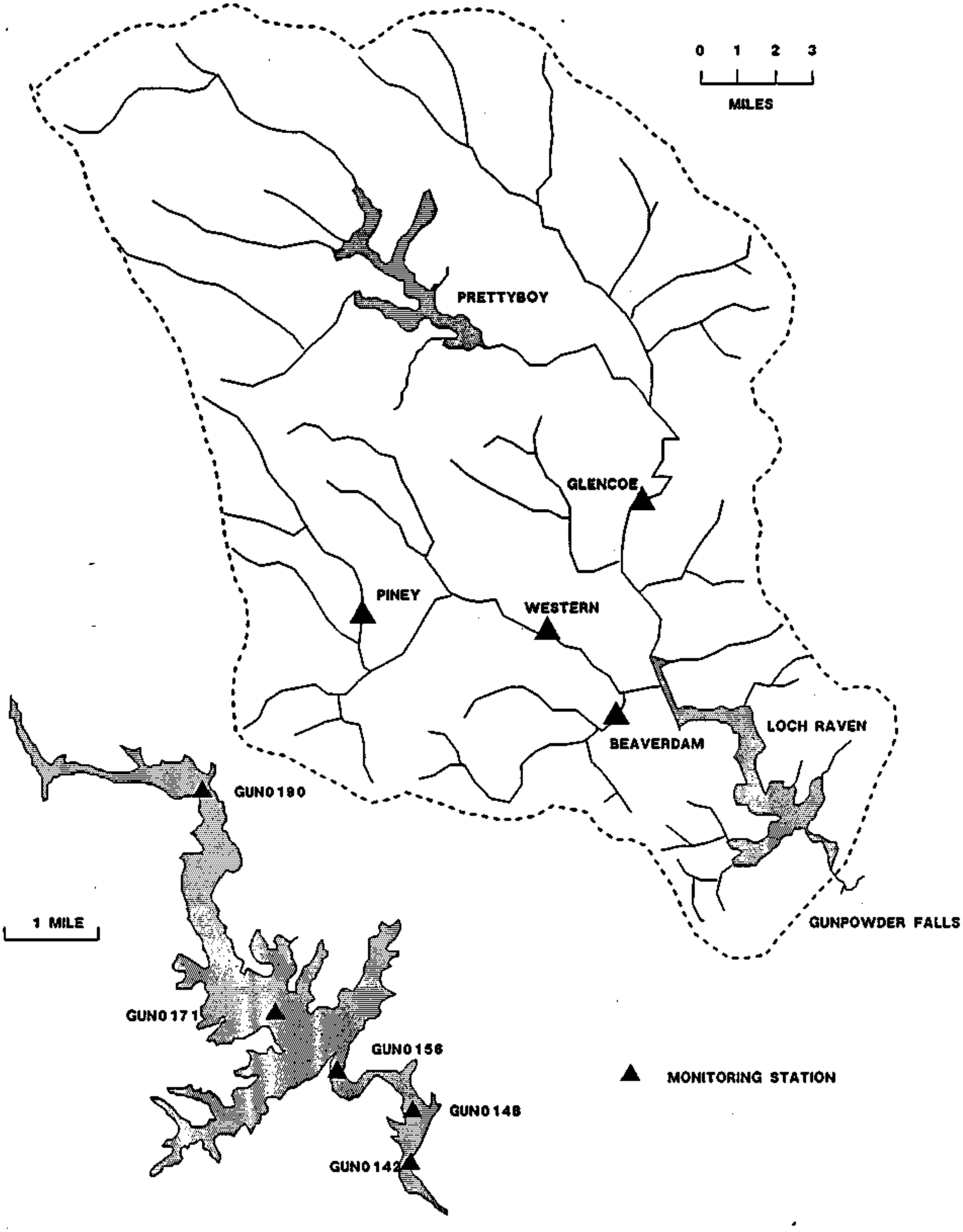
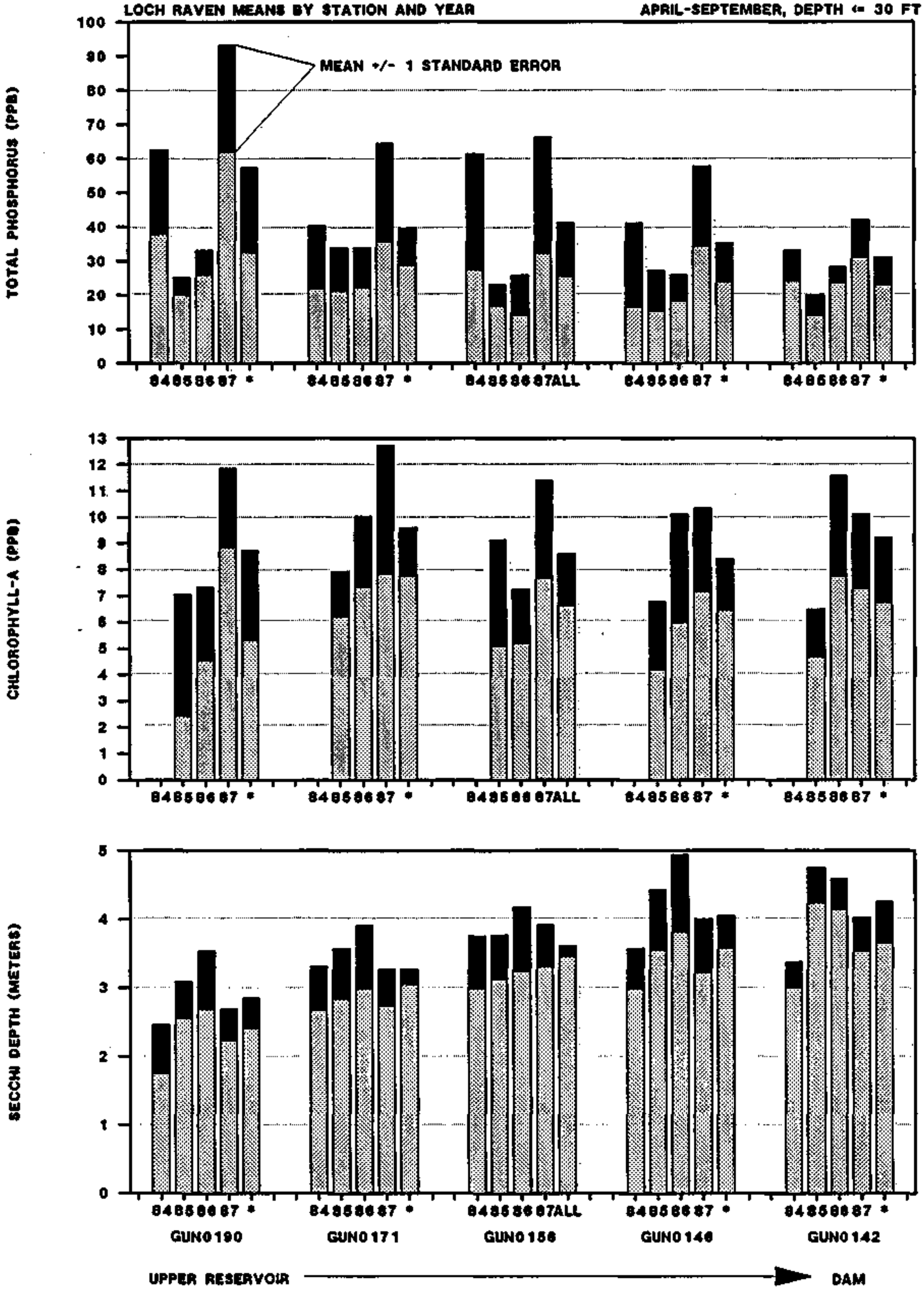


Table 12
Loch Raven Epilimnetic Means vs. Station and Year

		TOTAL PHOSPHORUS (PPB)			CHLOROPHYLL-A (PPB)			SECCHI DEPTH (METERS)		
STATION	YEAR	N	MEAN	CV(MEAN)	N	MEAN	CV(MEAN)	N	MEAN	CV(MEAN)
UPPER RESERVOIR - POWER LINES										
GUN0190	84	8	50.1	0.246				8	2.11	0.169
GUN0190	85	4	22.5	0.111	3	4.7	0.489	5	2.83	0.093
GUN0190	86	5	29.5	0.121	6	5.9	0.235	6	3.11	0.137
GUN0190	87	6	77.5	0.201	6	10.3	0.146	6	2.47	0.092
	ALL	23	44.9	0.275	15	7.0	0.244	25	2.63	0.083
MID RESERVOIR - PICNIC/GOLF										
GUN0171	84	8	31.1	0.295				8	2.99	0.107
GUN0171	85	4	27.5	0.229	3	7.1	0.121	4	3.21	0.115
GUN0171	86	5	28.0	0.208	6	8.7	0.155	6	3.45	0.134
GUN0171	87	6	50.0	0.288	6	10.3	0.238	6	3.00	0.088
	ALL	23	34.2	0.156	15	8.7	0.107	24	3.16	0.034
LOCH RAVEN DRIVE - #1 BRIDGE										
GUN0156	84	7	44.3	0.381				7	3.37	0.113
GUN0156	85	5	20.0	0.158	5	7.1	0.285	7	3.44	0.095
GUN0156	86	4	20.0	0.289	6	6.2	0.165	6	3.71	0.125
GUN0156	87	6	49.2	0.345	6	9.5	0.195	6	3.61	0.085
	ALL	22	33.4	0.233	17	7.6	0.130	26	3.53	0.022
2000 FT ABOVE DAM										
GUN0146	84	7	28.9	0.423				9	3.28	0.091
GUN0146	85	4	21.3	0.278	3	5.5	0.236	5	3.99	0.109
GUN0146	86	5	22.0	0.170	6	8.0	0.256	6	4.38	0.128
GUN0146	87	6	45.8	0.256	6	8.7	0.183	6	3.61	0.108
	ALL	22	29.5	0.194	15	7.4	0.133	26	3.82	0.062
INTAKE - NEAR DAM										
GUN0142	84	20	28.7	0.159				22	3.19	0.058
GUN0142	85	15	17.0	0.172	7	5.6	0.165	20	4.49	0.057
GUN0142	86	19	25.8	0.093	6	9.7	0.198	24	4.37	0.050
GUN0142	87	21	36.5	0.150	11	8.7	0.163	23	3.78	0.064
	ALL	75	27.0	0.149	24	8.0	0.154	89	3.96	0.075
RESERVOIR - AVERAGE OF YEARLY MEANS BY STATION										
ALL	84		36.6						2.99	
ALL	85		21.7			6.0			3.59	
ALL	86		25.1			7.7			3.80	
ALL	87		51.8			9.5			3.30	
ALL	ALL		33.8			7.7			3.42	

APRIL-SEPTEMBER, MEDIANS OF SAMPLES BETWEEN 0 AND 30 FEET

Figure 14
Loch Raven Epilimnetic Means vs. Station and Year



Variable		Mean	CV(MEAN)	67% Confidence Limit
Total P	(ppb)	27.0	.149	22.9 - 31.0
Chl-a	(ppb)	8.0	.154	6.8 - 9.2
Secchi	(meters)	4.0	.075	3.7 - 4.3

The phosphorus and chlorophyll-a levels suggest that the reservoir is at the mesotrophic/eutrophic boundary. The estimated mean phosphorus concentration is just above the target concentration of 26 ppb established for Loch Raven. Transparency is well within the mesotrophic range at the dam, but approaches the eutrophic boundary in the upper reservoir.

Based upon comparisons of seasonal means (Figure 14), spatial variations are less distinct than observed in many reservoirs (Walker, 1985) because of the relatively short hydraulic residence time of Loch Raven (averaging ~.24 years). Moving from the upper reservoir to the dam, average phosphorus concentration decreases from 45 to 27 ppb and transparency increases from 2.6 to 4.0 meters. These variations reflect sedimentation of phosphorus and inorganic turbidity supplied by the reservoir tributaries. Spatial variations in chlorophyll-a are minimal (range 7 to 8.7 ppb), probably as a result of the relatively high flushing rate.

Chlorophyll-a concentrations at the powerline station average slightly below those measured at downstream stations, despite the higher average phosphorus concentrations and lower average transparency at this station. This most likely reflects the fact that hydraulic residence time above the powerlines is insufficient to permit full biological response to ambient nutrient levels, a situation which is typical of reservoir inflow segments (Walker,1985). The most productive area of the reservoir is probably between the powerlines (GUN0190) and picnic/golf station (GUN0171) in the middle of the reservoir.

Yearly-mean phosphorus concentrations at the dam ranged from 17 ppb in 1985 to 37 ppb in 1987. Most stations had higher phosphorus levels and lower transparencies in 1984 and 1987, as compared with 1985 and 1986. These variations partially reflect higher inflows during the summers of

1984 and 1987, as illustrated in Figure 15. Two additional factors contributed to the substantially higher phosphorus concentrations observed in 1987:

(1) Scouring of stream channels associated with the return of high flows in 1987, following a period of deposition and limited souring during the 1985-1986 drought.

(2) Releases from upstream Prettyboy Reservoir (as partially reflected by the gauged flow at Glencoe, Figure 15) accounted for a smaller fraction of the total inflow to Loch Raven in 1987. The reservoir releases would be expected to have substantially lower phosphorus concentrations than runoff from other watersheds contributing directly to Loch Raven. This would tend to cause a higher average inflow concentration during 1987.

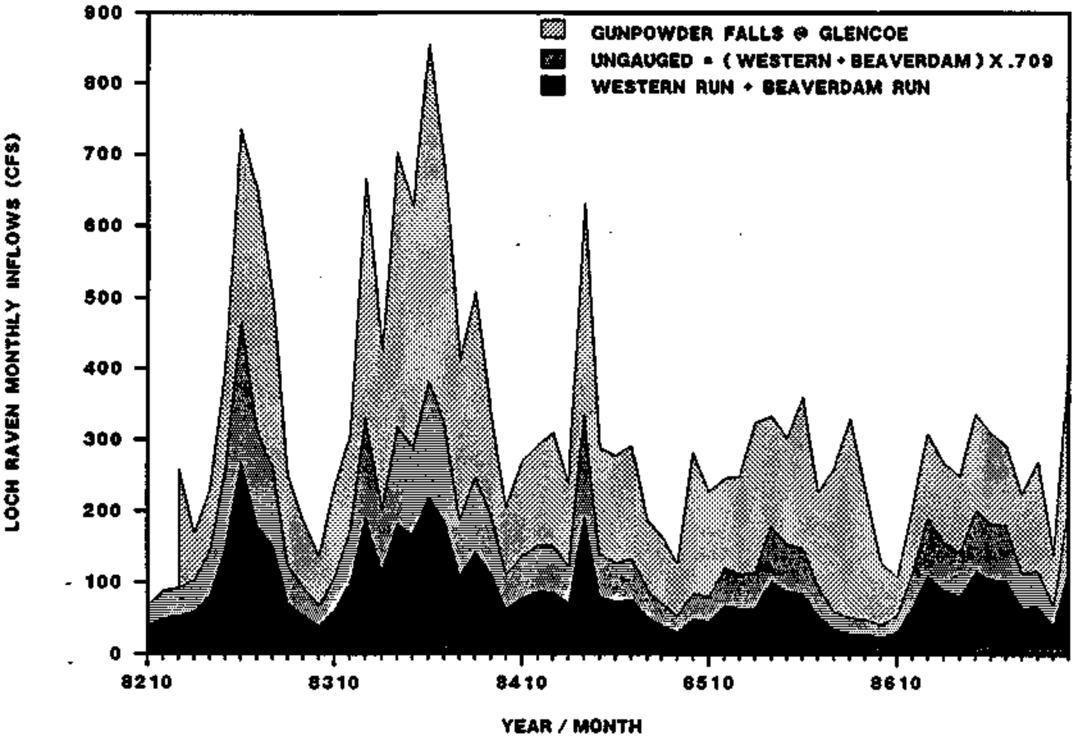
As discussed below, year-to-year variations attributed to hydrology or other natural factors have important implications for detecting changes in longterm mean reservoir conditions resulting from watershed management programs.

3.2 Variance Component Analysis

Variance components are useful for evaluating alternative sampling program designs from a statistical point of view (Walker,1980ab, Knowlton et al, 1984; Smeltzer et al, 1988). Within-year and among-year variance components have been estimated for each station and variable using a one-way analysis of variance (ANOVA) on logarithmic scales (Snedecor and Cochran,1967). Results are listed in Table 13 and displayed in Figure 16.

ANOVA results indicate significant year-to-year variations in phosphorus, chlorophyll-a, and transparency only at the upstream (powerline, GUN0190) and near-dam (intake, GUN0142) stations. The monthly sampling frequency may have been insufficient to define year-to-year

Figure 15
Monthly Inflows to Loch Raven Reservoir - 1983-1987



variations at the other three stations. Within-year variance components (date-to-date) are relatively uniform across stations.

Figure 16 compares within-year and among-year standard deviations with typical values derived from other data sets (Corps of Engineer Reservoirs, Minnesota Lakes, Vermont Lakes), as summarized by Smeltzer et al (1988). Figure 17 compares the Loch Raven within-year standard deviations with cumulative frequency distributions of within-year standard deviations computed from the reference data sets. Generally, the Loch Raven variance components for chlorophyll-a and transparency are typical of values derived from other lake and reservoir data sets. Loch Raven phosphorus variations are unusually high, however. The within-year standard deviations for phosphorus range from .6 to .9, as compared median values of .2 to .3 in other data sets. This 2-3-fold difference in standard deviation is equivalent to a 4-9-fold difference in variance. As illustrated in Figure 17, the Loch Raven values exceed the 98th percentiles of within-year standard deviations computed from the reference data sets, which include measurements from Corps of Engineer reservoirs which are similar to Loch Raven with respect to depth, flushing rate, and watershed characteristics.

The high variability of the phosphorus data from Loch Raven Reservoir is further illustrated by the time series plots in Figures 18 and 19. This variability imposes severe limitations on the tracking of reservoir responses to watershed management programs designed to reduce phosphorus loadings by 10-30%. The within-year standard deviations reflect variations from one sampling date to the next at a given station. A number of factors may contribute to the high variability:

(1) true temporal variations in reservoir concentrations, attributed to fluctuations in flow and other natural factors.

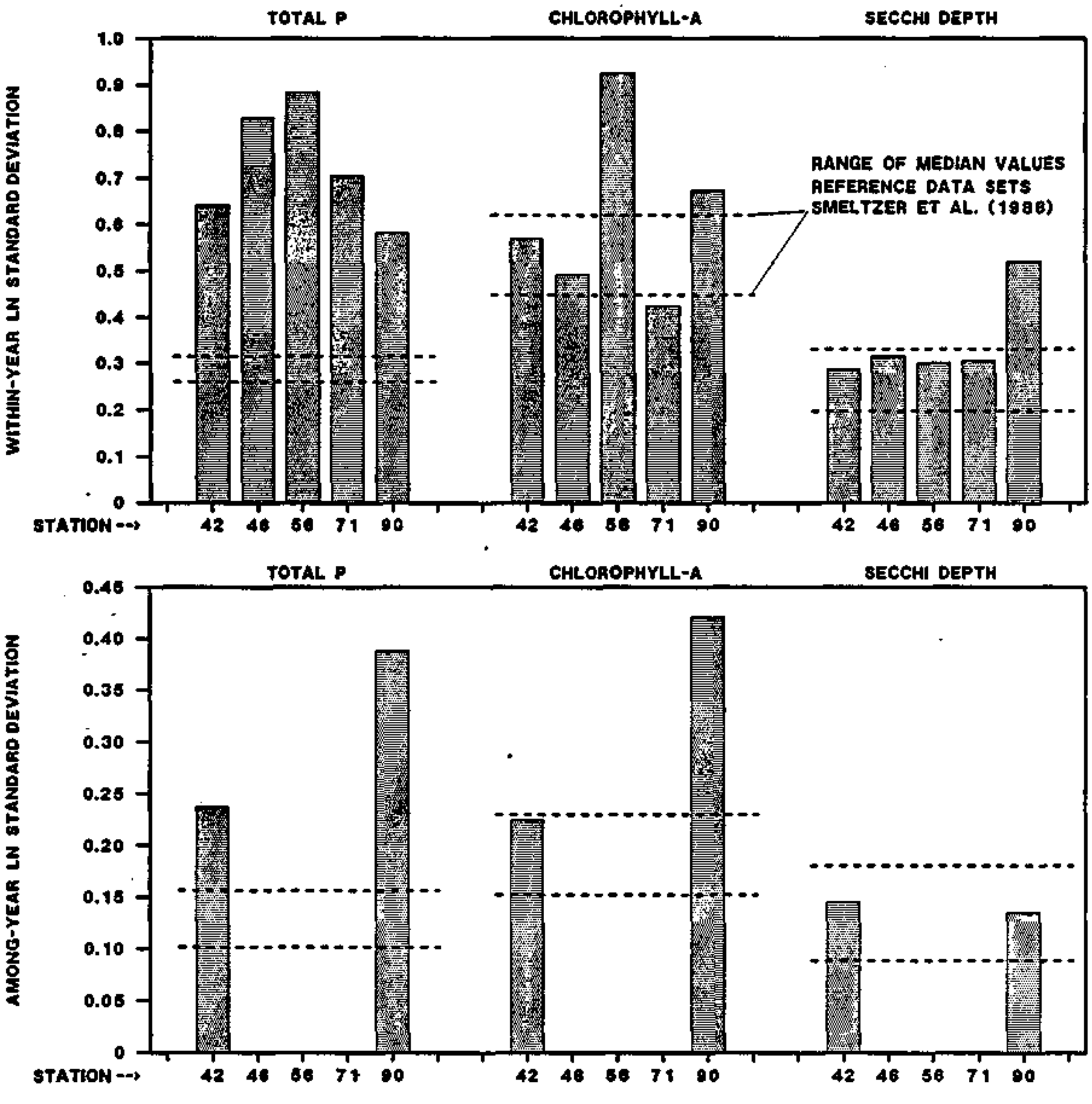
(2) spatial variability within the mixed layer. Concentration variations within the 0-30 foot depth range may be unusually high due to interflows or other hydrodynamic factors, although

Table 13
Loch Raven Variance Components

VARIABLE/	TOTAL		.... YEAR-TO-YEAR			... WITHIN-YEAR ...					GEOM.	MEAN	RESIDUAL AUTO-	AVERAGE SAMPLES/	SAMPLE INTERVAL
STATION	SAMPLES	YRS	MEAN SQ	VAR COMP	STD DEV	DOF	MEAN SQ	STD DEV	F	PROB(>F)	MEAN	CV	CORREL.	YEAR	DAYS
TOTAL PHOSPHORUS (PPB)															
GUN0142	75	4	1.4770	0.0571	0.239	71	0.4112	0.641	3.59	0.018	22.4	0.141	0.120	18.8	9.7
GUN0146	22	4	0.4895	-0.0359	0.000	18	0.6841	0.827	0.72	0.558	22.7	0.150	-0.121	5.5	33.1
GUN0156	22	4	0.4963	-0.0523	0.000	18	0.7800	0.883	0.64	0.604	24.7	0.151	-0.053	5.5	33.1
GUN0171	23	4	0.2640	-0.0414	0.000	19	0.4968	0.705	0.53	0.670	27.7	0.107	0.067	5.8	31.7
GUN0190	23	4	1.2448	0.1611	0.401	19	0.3387	0.582	3.68	0.030	38.4	0.236	0.111	5.8	31.7
CHLOROPHYLL-A (PPB)															
GUN0142	24	3	0.7294	0.0525	0.229	21	0.3245	0.570	2.25	0.129	6.93	0.176	-0.155	8.0	22.8
GUN0146	15	3	0.2121	-0.0060	0.000	12	0.2408	0.491	0.88	0.558	6.97	0.119	-0.146	5.0	36.4
GUN0156	17	3	0.7455	-0.0191	0.000	14	0.8534	0.924	0.87	0.558	6.11	0.212	-0.199	5.7	32.1
GUN0171	15	3	0.0717	-0.0225	0.000	12	0.1796	0.424	0.40	0.684	8.25	0.069	-0.084	5.0	36.4
GUN0190	15	3	1.3369	0.1845	0.429	12	0.4514	0.672	2.96	0.089	6.05	0.305	-0.173	5.0	36.4
SECCHI DEPTH (METERS)															
GUN0142	89	4	0.5495	0.0210	0.145	85	0.0822	0.287	6.68	0.001	3.77	0.079	0.575	22.3	8.2
GUN0146	26	4	0.0967	-0.0004	0.000	22	0.0990	0.315	0.98	0.576	3.59	0.061	0.010	6.5	28.0
GUN0156	26	4	0.0123	-0.0121	0.000	22	0.0905	0.301	0.14	0.937	3.40	0.022	-0.140	6.5	28.0
GUN0171	24	4	0.0233	-0.0118	0.000	20	0.0926	0.304	0.25	0.860	3.02	0.031	0.008	6.0	30.3
GUN0190	25	4	0.3798	0.0177	0.133	21	0.2705	0.520	1.40	0.269	2.34	0.124	-0.331	6.3	29.1

APRIL-SEPTEMBER, 1984-1987, MEDIANS OF SAMPLES <= 30 FT

Figure 16
Within-Year and Among-Year Variance Components for Loch Raven Reservoir



LOCH RAVEN RESERVOIR, 1984-1987, DEPTH <=30 FT, APRIL-SEPT

Figure 17
Variance Component Distributions - Reference Data Sets

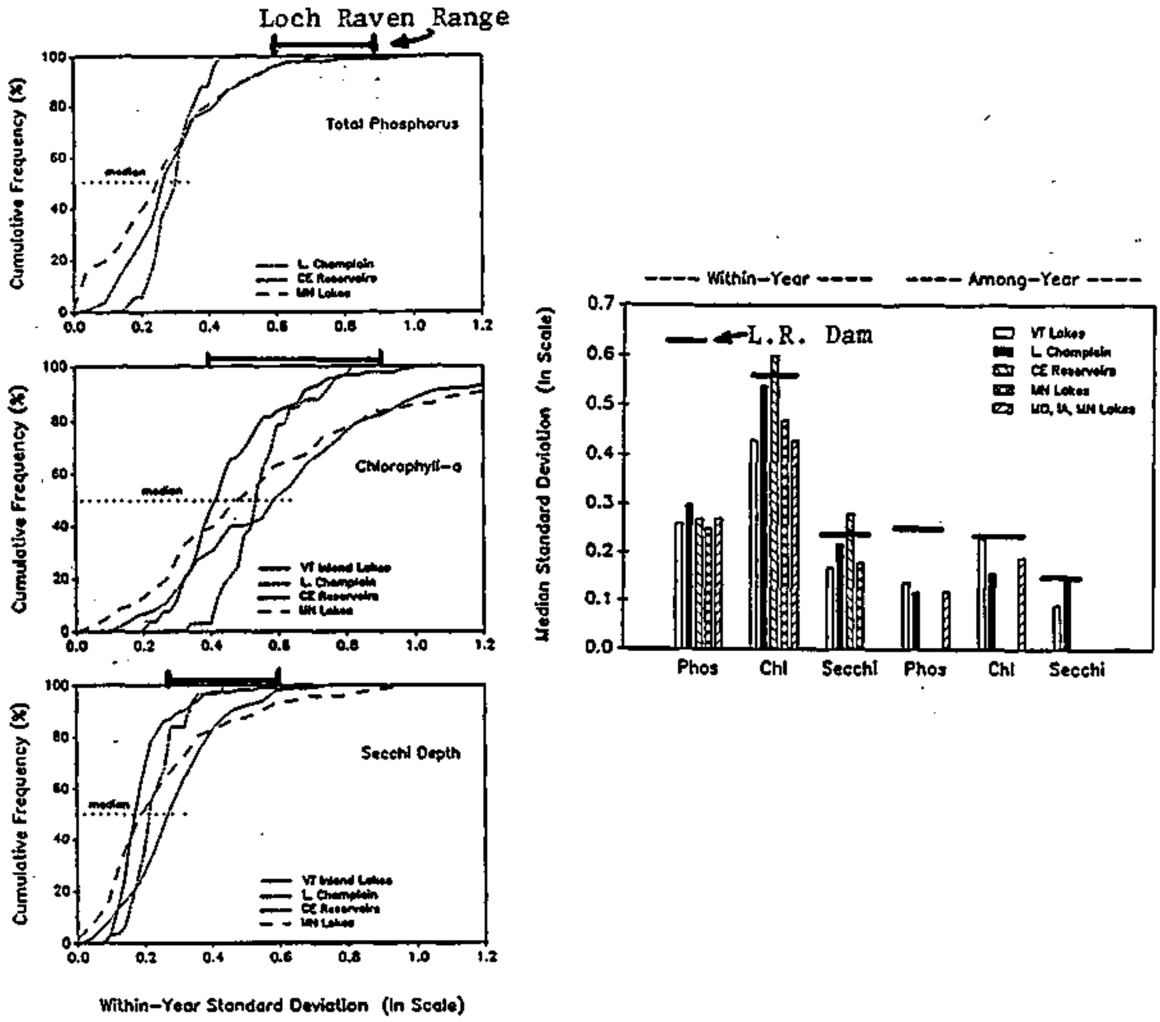


Figure 18
Total Phosphorus Time Series for Each Station

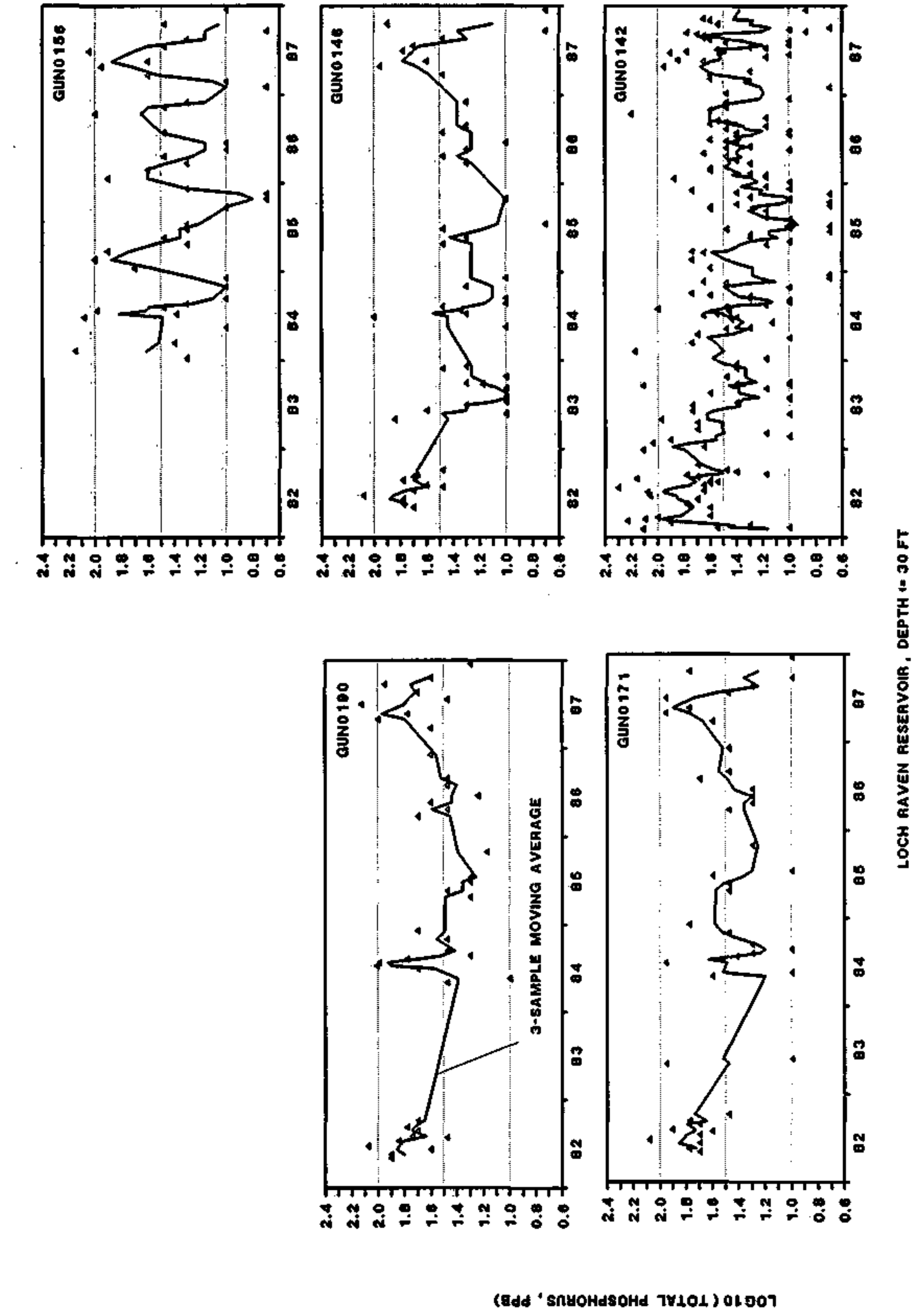
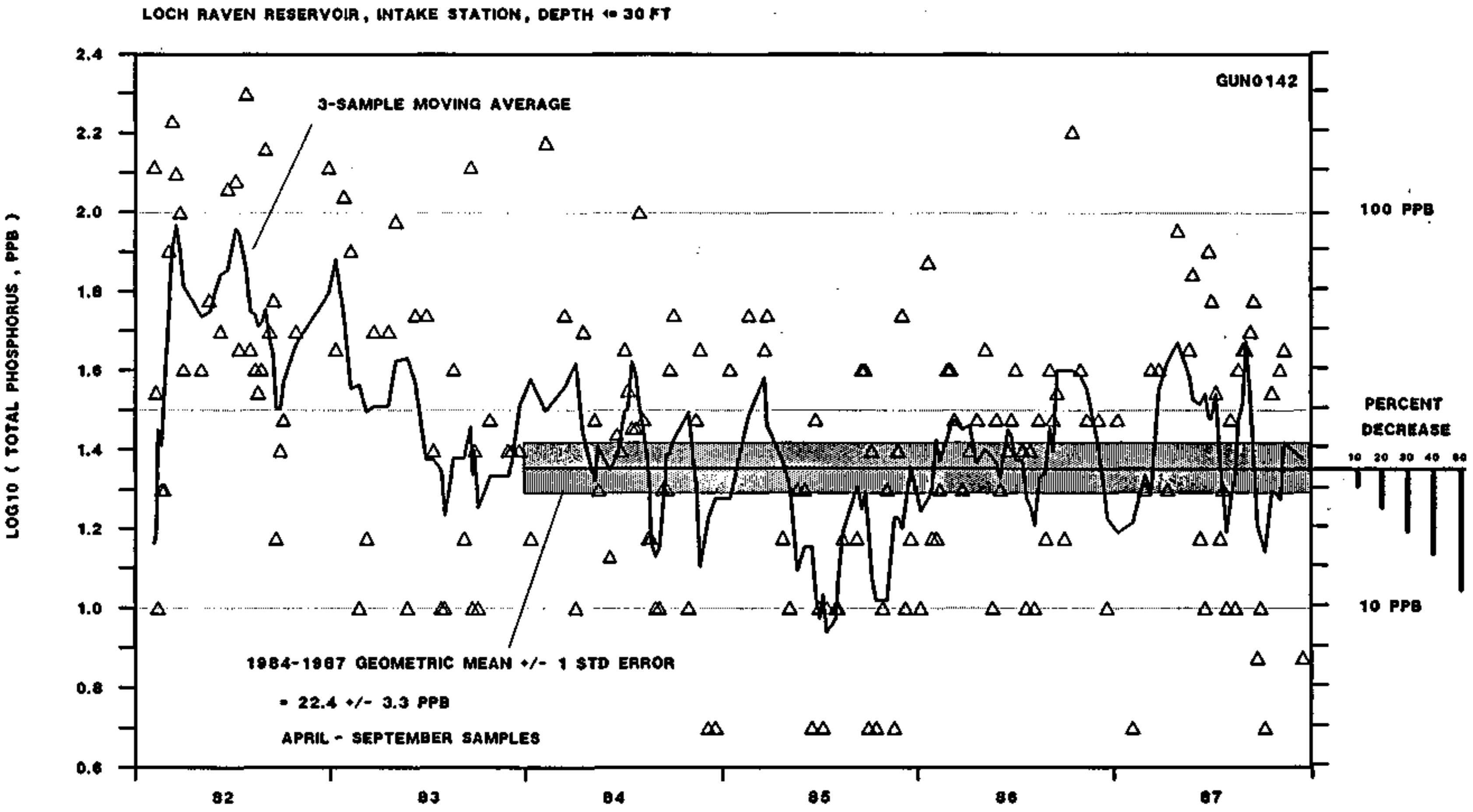


Figure 19
Intake Total Phosphorus Time Series



the historical data reveal no consistent vertical patterns within this depth range.

(3) sampling error.

(4) analytical error. Analysis of total phosphorus concentration is very difficult in the relatively low ranges typical of reservoir environments (vs. high ranges typical of streams and wastewater effluents).

(5) data manipulation/reporting error.

Given that the chlorophyll-a and transparency variance components are well within normal ranges, it seems unlikely that the unusually high phosphorus variance is "real" (1). A cursory review of the data indicates that sample-to-sample variations within the 0-30 ft range on a given date are unusually large. Based upon 300 samples taken on 75 dates at the intake station, the sample-to-sample standard deviation over the 0-30 ft depth range is .56 ($\log_e$ scale). In a data set derived Missouri, Iowa, and Minnesota lakes, Knowlton et al (1984) found a median sample-to-sample variation of .073 for total phosphorus. Analysis of replicate samples and a thorough review of sampling procedures, laboratory procedures, and reporting procedures would help to further define major sources of this variance, so that steps can be taken to minimize then in future monitoring.

3.3 Detection of Changes

The variance components estimated above provide a basis for statistical evaluation of alternative monitoring program designs. Appendix A describes LRSD.WK1, a Lotus-123 worksheet which has been developed to for this purpose. The program uses a modified version of the methodology developed by Smeltzer et al. (1988). Survey design variables include duration (number of years), season length (days per year), and sampling interval (days between samples). With the variance components estimated above for each variable and station, LRSD.WK1 can be used to estimate the precision of the longterm geometric mean derived from a given survey design and to estimate the "power" for detecting changes in the longterm mean. The precision of the geometric mean is slightly higher than the precision of the arithmetic mean for variables which are lognormally distributed. For purposes of survey design, however, the distinction between the two is usually negligible (i.e., the coefficient of variation (CV) of the geometric mean ~ the CV of the arithmetic mean).

As described by Lettenmaier (1976), "power" is an extremely important characteristic of a monitoring program. For the present purposes, "power" can be defined as the probability of detecting a given percent change in the longterm geometric mean which occurs between two time periods. "Detection" is defined as rejection of the null hypothesis in a t-test at a significance level of .05 (for a change in a specified direction) or .10 (for a change in either direction). Using the equations given in Appendix A, **LRSD.WK1** estimates the power associated with a given monitoring program design, set of variance components, and percent change. Other output statistics include the coefficient of variation of the longterm mean, 95% confidence factors for the geometric mean, and minimum detectable change (Spooner et al., 1987).

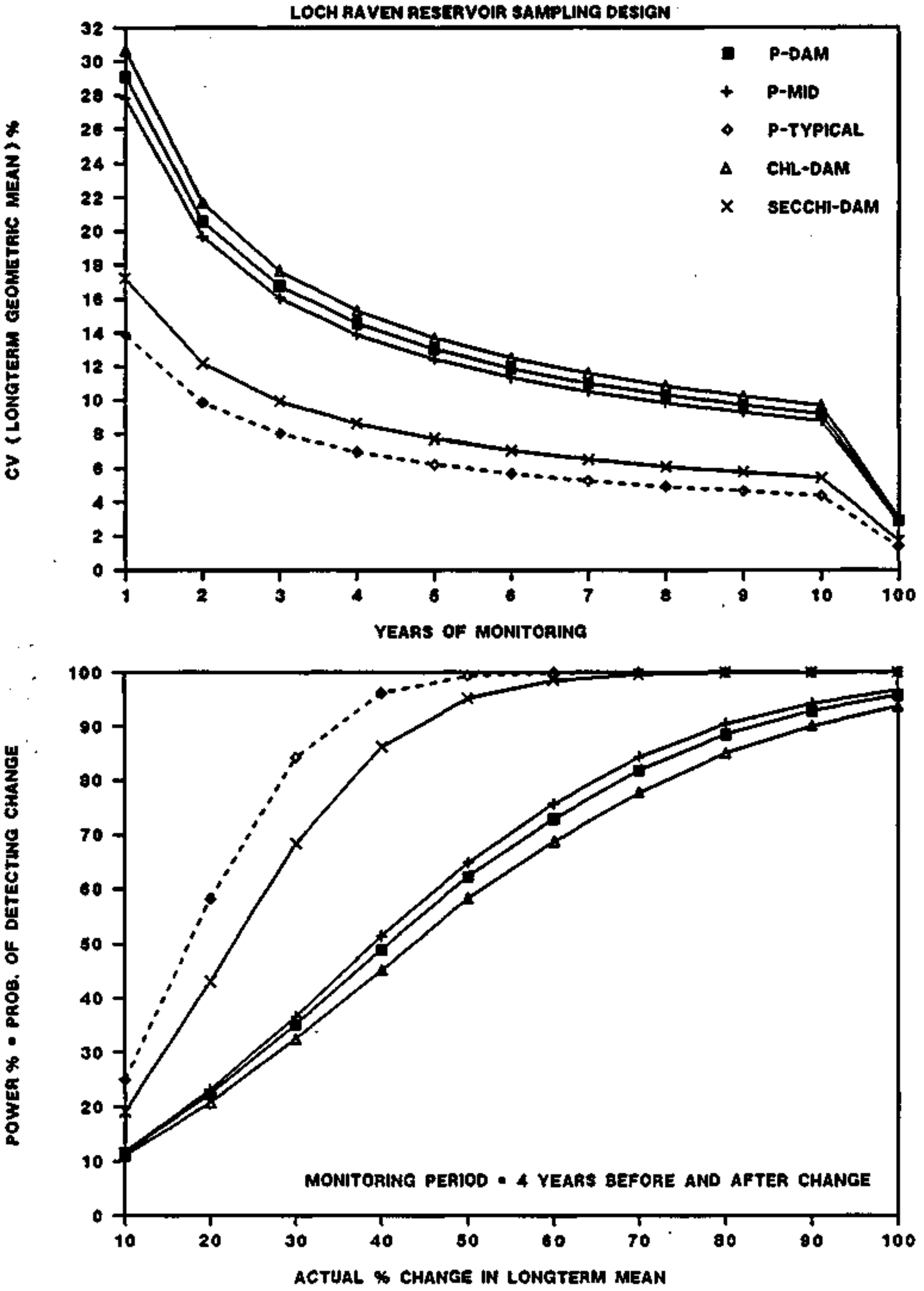
LRSD.WK1 output for Loch Raven Reservoir sampling program designs is given in Table 14 and Figure 20. Each column in the worksheet represents a separate case. Five cases have been run to illustrate key points:

P-DAM = total phosphorus, intake station (GUN0142)
P-MID = total phosphorous, mid reservoir (GUN0171)
P-TYPICAL = total phosphorus, median variance components from other lake data sets (Smeltzer et al.,1988) and intake sampling frequencies
CHL-DAM = chlorophyll-a, intake station
SECCHI-DAM = secchi depth, intake station

Table 14
LRSD Output for 1984-87 Conditions

```
LAKE/RESERVOIR SAMPLING DESIGN      LRSD-1.0    W. WALKER      DEC 1988
Press 'ALT-G' for graphs
INPUTS.................... LOCH RAVEN VARIANCE COMPONENTS
case labels ------------>     P-DAM    P-MID    P-TYP  CHL-DAM SECCHI-DA
among-year ln std dev         0.239        0     0.12    0.229    0.145
within-year ln std dev        0.641    0.705     0.27     0.57    0.287
lag 1-day auto-correlation      0.8      0.8      0.8      0.8      0.9
sampling duration = N (yrs)       4        4        4        4        4
sampling season (days/year)     182      182      182      182      182
sampling interval (days)         10       30       10       23        8
hypothet. step change C (%)      28       28       28       28       28

OUTPUTS..................
power for detecting C %        32.6     32.6     80.0     30.2     64.0
minimum detectable change %    28.9     28.8     15.0     30.4     18.4
cv (longterm geom. mean ) %    14.6     14.3      6.9     15.3      8.6
cv ( yearly geom. mean ) %     16.6     28.7      7.0     20.4      9.3
95% confid. factor - low      0.784    0.782    0.890    0.771    0.865
95% confid. factor - high     1.276    1.278    1.123    1.297    1.156
sample saturation %            71.3     29.1     71.3     37.6     93.9
total samples per season       18.2      6.1     18.2      7.9     22.8
total samples per N years      72.8     24.3     72.8     31.7     91.0

mdc% vs. years of monitoring for N years of baseline data
                         1     41.7     41.6     22.7     43.6     27.5
                         2     34.2     34.1     18.1     35.8     22.0
                         3     30.8     30.7     16.1     32.4     19.7
                         4     28.9     28.8     15.0     30.4     18.4
                         5     27.7     27.6     14.3     29.1     17.5
                         6     26.8     26.7     13.8     28.1     16.9
                         7     26.1     26.0     13.4     27.4     16.5
                         8     25.6     25.5     13.2     26.9     16.1
                         9     25.2     25.1     12.9     26.5     15.8
                        10     24.8     24.8     12.7     26.1     15.6
                       100     21.8     21.7     11.1     23.0     13.6

cv (longterm geometric mean) % vs. years of monitoring
                         1     29.1     28.7     13.9     30.6     17.2
                         2     20.6     20.3      9.8     21.7     12.2
                         3     16.8     16.5      8.0     17.7      9.9
                         4     14.6     14.3      6.9     15.3      8.6
                         5     13.0     12.8      6.2     13.7      7.7
                         6     11.9     11.7      5.7     12.5      7.0
                         7     11.0     10.8      5.3     11.6      6.5
                         8     10.3     10.1      4.9     10.8      6.1
                         9      9.7      9.6      4.6     10.2      5.7
                        10      9.2      9.1      4.4      9.7      5.4
                       100      2.9      2.9      1.4      3.1      1.7

power % vs. step change % for N years of monitoring before and after
                        10     11.6     11.6     25.0     11.0     19.2
                        20     22.4     22.3     58.1     20.8     43.0
                        30     35.2     35.2     84.3     32.6     68.3
                        40     49.0     49.2     96.2     45.1     86.2
                        50     62.3     62.7     99.3     58.2     95.2
                        60     73.0     73.4     99.9     68.7     98.5
                        70     81.9     82.3    100.0     77.7     99.6
                        80     88.4     88.7    100.0     84.9     99.9
                        90     92.8     93.0    100.0     90.1    100.0
                       100     95.7     95.8    100.0     93.6    100.0

power % vs. years of monitoring for N yrs of baseline data and change C%
                         1     18.6     17.9     46.8     16.9     35.3
                         2     25.2     24.2     64.8     22.7     49.5
                         3     29.6     28.4     74.1     26.6     58.7
                         4     32.7     31.4     79.7     29.3     64.1
                         5     34.9     33.7     83.4     31.4     67.9
                         6     36.7     35.4     85.9     33.0     70.7
                         7     38.1     36.7     87.7     34.3     72.9
                         8     39.3     37.9     89.1     35.3     74.6
                         9     40.3     38.8     90.1     36.2     76.0
                        10     41.1     39.6     90.9     36.9     77.2
                       100     50.8     48.9     96.5     45.1     87.3
```

Figure 20
CV(Mean) and Power Curves for 1984-1987 Variance Components



Variance components (expressed in terms of standard deviations) and sampling frequencies have been derived from historical monitoring data, as summarized in Table 13.

Figure 20 shows that the simulated cases fall into two general groups:

LOW-PRECISION: P-DAM, P-MID, CHLA-DAM
HIGH-PRECISION: P-TYPICAL, SECCHI-DAM

For a baseline monitoring period of 4 years (1984-1987), the CV of the longterm geometric mean for the low-precision cases ranges from 14 to 17%, as compared with 8 to 10% for the high-precision cases.

Power statistics have been evaluated for a hypothetical step change of 28% in the longterm mean, which corresponds to a reduction in phosphorus from a 36 to 26 ppb, the established goal of the Loch Raven reservoir management program (Stack and Gottfredson, 1980). The power statistics indicate that the probability of detecting a 28% change in the mean based upon a 4-year sampling period is only 30-33% for the low-precision cases vs. 64-80% for the high-precision cases. This indicates, for example, that if a 28% reduction in the longterm mean phosphorus concentration at Loch Raven intake occurred at the beginning of 1988 and if the sampling program were continued through 1991 with at the same frequencies and variance components characteristic of the 1984-1987 period, the probability of detecting the 28% change between the 1984-87 and 1988-91 periods would be 33%. If a more drastic change of 50% were to occur (which would be catastrophic for the water supply if it were an increase), the probability of detecting the change would be 58-63% for the low-precision cases vs. 95-99% for the high-precision cases.

The above results reveal the statistical difficulties associated with detecting small changes in reservoir conditions, given the characteristics of the Loch Raven data sets. As discussed above, an initial objective of the reservoir management program was to reduce the longterm average phosphorus concentration in Loch Raven by 28%. The power curves in Figure 20 indicate that detection of such a change would be difficult (probability of detection ~33%), given the monitoring frequencies and phosphorus variance components observed during 1984-1987. Detecting a 28% change would be more feasible in the case of the Secchi depth (probability of detection ~ 64%) or if phosphorus variance components were more typical of other lake/reservoir data sets (probability of detection ~ 80%).

A somewhat different, though equally relevant statistical issue is whether the longterm mean calculated from a given period of record is less than a fixed target concentration (in this case, 26 ppb). The arithmetic mean phosphorus concentration calculated for 1984-1987 is 27 ppb (Table 12). **LRSD.WK1** output (Table 14) indicates a lower confidence factor of .784 for the geometric mean phosphorus concentration at the intake station. This means that in order to be 95% sure that true mean concentration is less than the target mean, the measured mean would have to be less than or equal to .784 x 26 or 20.4 ppb. This assumes that the CV of the arithmetic mean equals the CV of the geometric mean; in fact, the arithmetic CV is slightly higher and the confidence factor, slightly lower than that estimated by the program. The difference between 26 ppb and 20.4 ppb (22%) is another useful measure of uncertainty. In contrast, the lower confidence factor for typical phosphorus variance components would be .89 or 23.1 ppb. The unusually high variability in the phosphorus data significantly reduces the feasibility of making statistically definitive statements regarding achievement of reservoir management objectives.

3.4 Reservoir Monitoring Program Design

Other sets of **LRSD.WK1** simulations illustrate the sensitivity to sampling interval for observed (Table 15) and typical (Table 16) phosphorus variance components. Sampling frequencies range from bimonthly (60-day intervals) to semi-weekly (4-day intervals). Power statistics are plotted in Figure 21. For each set of variance components, the benefits of decreasing sampling intervals below two weeks are minimal, based upon the fact that the power curves for biweekly, weekly, and semi-weekly

Table 15
LRSD Sensitivity to Sampling Interval for Loch Raven Phosphorus Variance Components

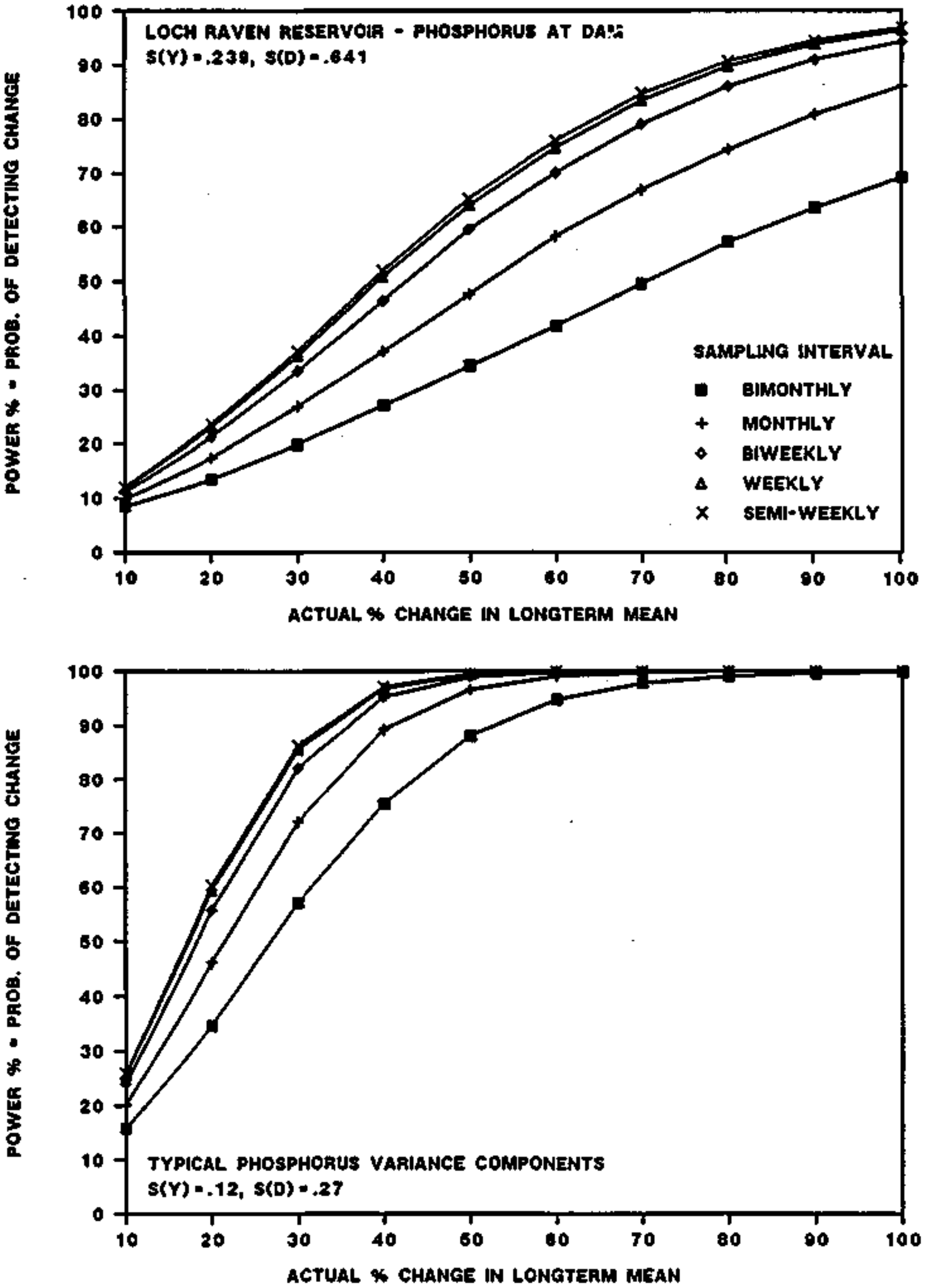
```
LAKE/RESERVOIR SAMPLING DESIGN      LRSD-1.0    W. WALKER      DEC 1988
Press 'ALT-G' for graphs
INPUTS...................  LOCH RAVEN PHOSPHORUS VARIANCE COMPONENTS
case labels ------------>  BIMONTHLY MONTHLY BIWEEKLY   WEEKLY SEMI-WEEK
among-year ln std dev          0.239    0.239    0.239    0.239    0.239
within-year ln std dev         0.641    0.641    0.641    0.641    0.641
lag 1-day auto-correlation       0.8      0.8      0.8      0.8      0.8
sampling duration = N (yrs)        4        4        4        4        4
sampling season (days/year)      182      182      182      182      182
sampling interval (days)          60       30       14        7        4
hypothet. step change C (%)       28       28       28       28       28

OUTPUTS..................
power for detecting C %         18.5     25.0     31.0     33.6     34.4
minimum detectable change %     41.3     34.3     29.9     28.3     27.9
cv (longterm geom. mean ) %     21.9     17.7     15.1     14.2     14.0
cv ( yearly geom. mean ) %      36.8     26.1     18.5     15.4     14.5
95% confid. factor - low       0.675    0.739    0.776    0.789    0.792
95% confid. factor - high      1.482    1.354    1.289    1.268    1.262
sample saturation %             14.6     29.1     57.6     83.0     93.6
total samples per season         3.0      6.1     13.0     26.0     45.5
total samples per N years       12.1     24.3     52.0    104.0    182.0

mdc% vs. years of monitoring for N years of baseline data
                          1     56.9     48.5     43.0     40.9     40.4
                          2     47.9     40.2     35.3     33.5     33.0
                          3     43.7     36.4     31.9     30.2     29.8
                          4     41.3     34.3     29.9     28.3     27.9
                          5     39.7     32.8     28.6     27.1     26.7
                          6     38.5     31.8     27.7     26.2     25.8
                          7     37.6     31.1     27.0     25.6     25.2
                          8     36.9     30.5     26.5     25.1     24.7
                          9     36.4     30.0     26.1     24.7     24.3
                         10     36.0     29.6     25.7     24.3     24.0
                        100     31.9     26.1     22.6     21.4     21.0

cv (longterm geometric mean) % vs. years of monitoring
                          1     43.9     35.4     30.2     28.4     28.0
                          2     31.0     25.0     21.4     20.1     19.8
                          3     25.3     20.4     17.5     16.4     16.1
                          4     21.9     17.7     15.1     14.2     14.0
                          5     19.6     15.8     13.5     12.7     12.5
                          6     17.9     14.4     12.3     11.6     11.4
                          7     16.6     13.4     11.4     10.8     10.6
                          8     15.5     12.5     10.7     10.1      9.9
                          9     14.6     11.8     10.1      9.5      9.3
                         10     13.9     11.2      9.6      9.0      8.8
                        100      4.4      3.5      3.0      2.8      2.8

power % vs. step change % for N years of monitoring before and after
                         10      8.5      9.9     11.3     11.9     12.0
                         20     13.5     17.5     21.3     23.1     23.6
                         30     19.9     27.0     33.5     36.3     37.1
                         40     27.0     37.0     46.4     50.8     51.9
                         50     34.4     47.7     59.5     64.0     65.2
                         60     41.8     58.2     70.1     74.8     76.1
                         70     49.5     66.8     79.0     83.5     84.7
                         80     57.3     74.4     86.1     89.8     90.7
                         90     63.6     80.9     91.0     93.8     94.5
                        100     69.2     86.0     94.3     96.4     96.9

power % vs. years of monitoring for N yrs of baseline data and change C%
                          1     11.3     14.3     17.6     19.1     19.7
                          2     14.5     18.8     23.7     26.0     26.7
                          3     16.8     21.8     27.7     30.4     31.3
                          4     18.5     24.0     30.5     33.5     34.4
                          5     19.9     25.6     32.7     35.8     36.8
                          6     21.0     26.9     34.3     37.6     38.6
                          7     21.8     28.0     35.6     39.0     40.1
                          8     22.6     28.8     36.7     40.2     41.3
                          9     23.2     29.6     37.5     41.2     42.4
                         10     23.7     30.2     38.3     42.1     43.3
                        100     29.6     36.6     46.9     51.7     53.2
```

Table 16

LRSD Sensitivity to Sampling Interval for Typical Phosphorus Variance Components

```
LAKE/RESERVOIR SAMPLING DESIGN       LRSD-1.0    W. WALKER       DEC 1988
Press 'ALT-G' for graphs
INPUTS....................    TYPICAL PHOSPHORUS VARIANCE COMPONENTS
case labels ------------>      BIMONTHLY   MONTHLY  BIWEEKLY    WEEKLY SEMI-WEEK
among-year ln std dev               0.12      0.12      0.12      0.12      0.12
within-year ln std dev              0.27      0.27      0.27      0.27      0.27
lag 1-day auto-correlation           0.8       0.8       0.8       0.8       0.8
sampling duration = N (yrs)            4         4         4         4         4
sampling season (days/year)          182       182       182       182       182
sampling interval (days)              60        30        14         7         4
hypothet. step change C (%)           28        28        28        28        28

OUTPUTS..................
power for detecting C %             52.6      67.7      77.8      81.4      82.4
minimum detectable change %         21.2      17.6      15.5      14.8      14.6
cv (longterm geom. mean ) %          9.8       8.1       7.2       6.8       6.7
cv ( yearly geom. mean ) %          15.5      11.0       7.8       6.5       6.1
95% confid. factor - low           0.839     0.870     0.887     0.892     0.894
95% confid. factor - high          1.192     1.149     1.128     1.120     1.119
sample saturation %                 14.6      29.1      57.6      83.0      93.6
total samples per season             3.0       6.1      13.0      26.0      45.5
total samples per N years           12.1      24.3      52.0     104.0     182.0

mdc% vs. years of monitoring for N years of baseline data
                         1          31.4      26.3      23.3      22.3      22.1
                         2          25.3      21.1      18.6      17.8      17.6
                         3          22.7      18.8      16.6      15.9      15.7
                         4          21.2      17.6      15.5      14.8      14.6
                         5          20.2      16.7      14.7      14.1      13.9
                         6          19.5      16.2      14.2      13.6      13.4
                         7          19.0      15.7      13.8      13.2      13.0
                         8          18.6      15.4      13.5      12.9      12.8
                         9          18.3      15.1      13.3      12.7      12.5
                        10          18.1      14.9      13.1      12.5      12.4
                       100          15.8      13.0      11.4      10.9      10.7

cv (longterm geometric mean) % vs. years of monitoring
                         1          19.6      16.3      14.3      13.6      13.5
                         2          13.9      11.5      10.1       9.6       9.5
                         3          11.3       9.4       8.3       7.9       7.8
                         4           9.8       8.1       7.2       6.8       6.7
                         5           8.8       7.3       6.4       6.1       6.0
                         6           8.0       6.6       5.8       5.6       5.5
                         7           7.4       6.1       5.4       5.2       5.1
                         8           6.9       5.7       5.1       4.8       4.8
                         9           6.5       5.4       4.8       4.5       4.5
                        10           6.2       5.1       4.5       4.3       4.3
                       100           2.0       1.6       1.4       1.4       1.3

power % vs. step change % for N years of monitoring before and after
                        10          15.8      20.2      24.0      25.6      26.1
                        20          34.7      46.2      55.8      59.5      60.4
                        30          57.2      72.2      82.2      85.5      86.4
                        40          75.4      89.2      95.2      96.7      97.1
                        50          88.1      96.6      99.0      99.4      99.5
                        60          94.8      99.1      99.8      99.9      99.9
                        70          97.8      99.7     100.0     100.0     100.0
                        80          99.1      99.9     100.0     100.0     100.0
                        90          99.6     100.0     100.0     100.0     100.0
                       100          99.8     100.0     100.0     100.0     100.0

power % vs. years of monitoring for N yrs of baseline data and change C%
                         1          26.9      36.2      44.5      48.3      49.3
                         2          38.6      51.5      62.4      66.4      67.5
                         3          46.8      60.8      71.5      75.6      76.8
                         4          52.6      66.3      77.2      81.3      82.4
                         5          57.0      70.2      81.1      84.9      85.9
                         6          60.0      73.1      83.7      87.3      88.2
                         7          62.3      74.7      85.6      89.0      89.9
                         8          64.1      77.0      87.1      90.2      91.1
                         9          65.6      78.4      88.2      91.2      92.0
                        10          66.9      79.5      89.1      91.9      92.7
                       100          79.1      89.1      95.5      97.1      97.5
```

Figure 21
Power vs. Sampling Interval for Loch Raven and Typical Phosphorus Variance Components



MONITORING PERIOD = 4 YEARS BEFORE AND AFTER CHANGE intervals are very similar. This reflects the dominance of the year-to-year variance component in controlling the longterm mean at low sampling intervals (or high sampling frequencies). Serial correlation is another factor which reduces the effective sample size at low sampling intervals. For a Markov process (Lettenmaier,1976), the assumed 1-day serial correlation coefficient of .8 corresponds to a 10-day serial coefficient of $.8^{10} = .11$, as compared with the measured value of .12 for an average sampling interval of 9.7 days (Table 13). The impact of the unusually high phosphorus variance components for Loch Raven on power for detecting changes in the mean is illustrated by the differences between the two sets of curves in Figure 21.

Based upon the above analyses, the following recommendations are made to improve the resolution and efficiency of the data collection program in Loch Raven:

(1) Reduce the number of stations in the reservoir from 5 to 3 (Upper Reservoir - Powerlines; Mid Reservoir - Picnic-Golf; Lower Reservoir - Intakes);

(2) Sample at biweekly intervals;

(3) Continue to collect samples at 10 ft intervals at each station (as generally practiced during 1984-1987); this provides needed replication;

(4) Investigate potential sources of unusually high phosphorus variability, as outlined above; establish routine quality control program with ~10% replicate sampling to estimate sampling and analytical error variance components; improve resolution of total phosphorus analyses to at least +/- 5 ppb (vs. +/- 10 ppb).

Item (4) should have top priority. Statistical detection of future changes in phosphorus based upon comparison with historical data will be difficult because of the limitations of the historical data. With future reductions in the variability of the phosphorus data, however, it will become increasingly feasible to make definitive statements about whether the overall objective of the program (longterm average total phosphorus < 26 ppb) has been achieved, because such statements would not depend upon the historical data base. Refinements to the modeling approach discussed in the next section will further assist in tracking the progress of the watershed/reservoir management program.

4.0 LOAD/RESPONSE MODELING

Analysis of stream and reservoir data in previous sections reveal the capabilities and limitations of the monitoring programs from a statistical point of view. The linkage of the watershed and reservoir is critical to understanding the system and tracking the progress of management efforts. This linkage is analyzed below with the aid of a mass-balance model for predicting seasonal average reservoir conditions (phosphorus, chlorophyll-a, transparency) as a function of watershed flows, phosphorus loadings, and reservoir morphometry. The model provides important quantitative perspectives on hydrologic factors driving year-to-year variations in reservoir water quality.

4.1 Loading Estimates

Table 17 lists seasonal flow and phosphorus loading estimates for 1983 through 1987 at three monitoring stations in the Loch Raven watershed:

GLENCOE	Gunpowder Falls at Glencoe (Station GUN0258)
BEAVERDAM	Beaverdam Run (Station BEV0005)
WESTERN	Western Run (Station WGP0050)

Station locations are indicated in Figure 13. Together, these stations account for 81% of the total external drainage area above Loch Raven Reservoir. Flows and loadings for the ungauged portions of the watershed have been estimated by drainage area proportion relative to Beaverdam and

Table 17
Loch Raven Tributary Flows and Phosphorus Loads, 1983-1987

					.... TOTAL PHOSPHORUS........				.......DISSOLVED PHOSPHORUS........				.. AVAILABLE P ..	
		AREA	FLOW	RUNOFF	LOAD	CONC	EXPORT	CV	LOAD	CONC	EXPORT	CV	LOAD	CV
STATION	YEAR	KM2	HM3/YR	M/YR	KG/YR	PPB	KG/KM2-YR	-	KG/YR	PPB	KG/KM2-YR	-	KG/YR	-
GLENCOE	83	414.4	168.0	0.405	19186	114.2	46.3	0.173	5292	31.5	12.8	0.316	14400	0.193
GLENCOE	84	414.4	231.4	0.558	40856	176.6	98.6	0.156	9277	40.1	22.4	0.443	27627	0.239
GLENCOE	85	414.4	114.5	0.276	8107	70.8	19.6	0.155	3046	26.6	7.3	0.175	7319	0.125
GLENCOE	86	414.4	163.3	0.394	12345	75.6	29.8	0.160	3413	20.9	8.2	0.194	9278	0.130
GLENCOE	87	414.4	115.0	0.278	12029	104.6	29.0	0.221	3554	30.9	8.6	0.261	9388	0.177
BEAVERDA	83	54.1	35.1	0.649	9258	263.6	171.1	0.122	1233	35.1	22.8	0.234	4935	0.117
BEAVERDA	84	54.1	34.5	0.637	7355	213.5	136.0	0.136	1078	31.3	19.9	0.248	4071	0.129
BEAVERDA	85	54.1	14.7	0.272	2099	142.6	38.8	0.138	408	27.7	7.5	0.171	1314	0.109
BEAVERDA	86	54.1	11.1	0.205	818	73.8	15.1	0.199	287	25.9	5.3	0.183	707	0.136
BEAVERDA	87	54.1	21.7	0.401	3100	142.8	57.3	0.128	630	29.0	11.6	0.191	1983	0.114
WESTERN	83	154.9	77.2	0.498	27649	358.2	178.5	0.108	7341	95.1	47.4	1.020	20317	0.564
WESTERN	84	154.9	88.6	0.572	23653	266.9	152.7	0.110	6762	76.3	43.7	0.716	18115	0.410
WESTERN	85	154.9	32.4	0.209	4025	124.1	26.0	0.084	1680	51.8	10.8	0.473	3889	0.313
WESTERN	86	154.9	26.2	0.169	2296	87.5	14.8	0.086	963	36.7	6.2	0.109	2226	0.078
WESTERN	87	154.9	51.5	0.332	11988	233.0	77.4	0.146	3437	66.8	22.2	0.637	9196	0.368
UNGAUGED	83	147.5	79.3	0.537	26047	328.6	176.6	0.087	6051	76.3	41.0	0.874	17821	0.454
UNGAUGED	84	147.5	86.9	0.589	21883	252.0	148.4	0.090	5533	63.7	37.5	0.618	15658	0.336
UNGAUGED	85	147.5	33.3	0.226	4322	129.9	29.3	0.073	1473	44.3	10.0	0.382	3673	0.235
UNGAUGED	86	147.5	26.3	0.179	2197	83.4	14.9	0.082	882	33.5	6.0	0.094	2070	0.067
UNGAUGED	87	147.5	51.6	0.350	10648	206.2	72.2	0.119	2870	55.6	19.5	0.539	7890	0.304
TOTAL	83	770.9	359.6	0.466	82140	228.4	106.6	0.062	19916	55.4	25.8	0.468	57472	0.249
TOTAL	84	770.9	441.3	0.572	93748	212.4	121.6	0.077	22650	51.3	29.4	0.319	65471	0.172
TOTAL	85	770.9	194.9	0.253	18552	95.2	24.1	0.074	6607	33.9	8.6	0.168	16195	0.108
TOTAL	86	770.9	227.0	0.294	17657	77.8	22.9	0.113	5545	24.4	7.2	0.122	14281	0.086
TOTAL	87	770.9	239.8	0.311	37765	157.5	49.0	0.091	10490	43.7	13.6	0.271	28456	0.157

APRIL-SEPTEMBER

UNGAUGED = (BEAVERDAM + WESTERN) X .706

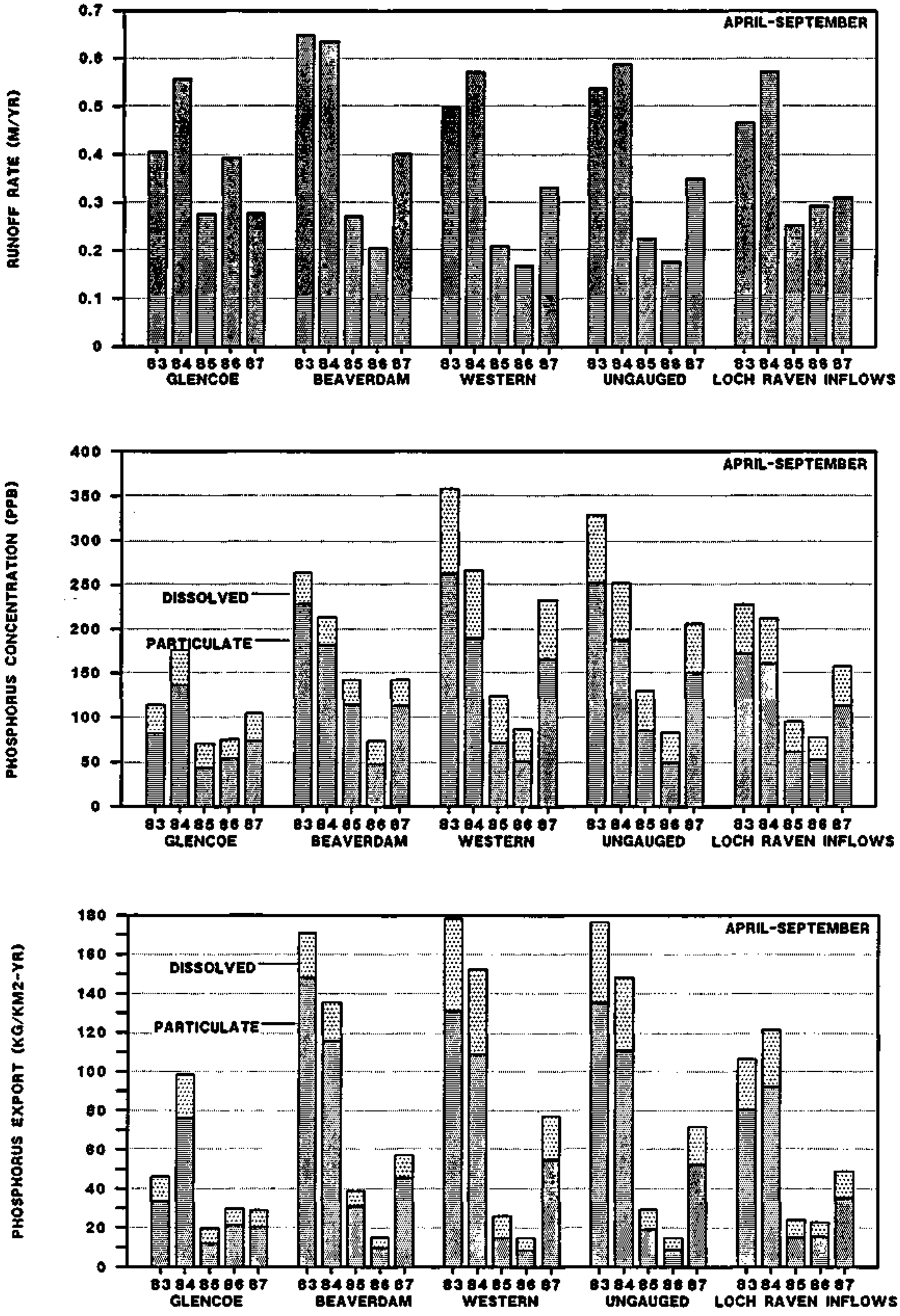
Western Runs (the Glencoe station is influenced by the flow regulating/phosphorus trapping functions of upstream Prettyboy Reservoir). Actual loadings from the ungauged portions of the watershed may be higher than those estimated because of the higher percentage of urban land uses in areas adjacent to the reservoir.

USGS gauges provide continuous records of flow at each of the above monitoring stations. The **FLUX** program has been applied to estimate total and dissolved phosphorus loadings for each station and year, based upon quality data collected by the Baltimore WQMO and the continuous daily flow record. Refinements to these estimates would be based upon 15-minute unit flows, which may provide more accurate estimates, based upon results for Piney Run stations.

The load calculation period has been restricted to April through September of each year. Seasonal phosphorus balances are more appropriate than annual balances for modeling reservoirs with relatively short hydraulic residence times, including Loch Raven (Walker,1985). Loading estimates for April-September of each year have been developed by mapping the flow concentration relationship developed from all April-September samples onto the flow record for April-September of each year (using the **FLUX** "Calculate Annual Flows" procedure). As such, the loading estimates reflect only the effects of year-to-year variations in hydrology and do not reflect changes in the flow/concentration relationships which may have occurred over time at these stations.

Figure 22 displays estimates of unit runoff, flow-weighted phosphorus concentration, and phosphorus export for each station and year. The time period includes two years of relatively high runoff (1983-1984), followed by three years of relatively low runoff (1985-1987). The average annual runoff rate for Maryland is ~.41 m/yr. Because of the strong flow/concentration relationships characteristic of these streams, the ~3-fold year-to-year variations in runoff at Beaverdam and Western Runs induce ~10-fold variations in phosphorus export. Because of the regulating and trapping functions of Prettyboy Reservoir, year-to-year variations at Glencoe station are less pronounced than those measured at

Figure 22
Loch Raven Tributary Runoff and Phosphorus Export 1983-1987



Beaverdam Run and Western Run. Runoff and phosphorus export at the latter two stations are remarkably similar.

Note that the export and runoff values listed in Table 17 and displayed in Figure 22 are average rates during April-September of each year. To calculate the mass of phosphorus discharged during a given April-September period, multiply the export rate by the duration in years (= 183/365).

Consistent with the strong relationships observed between flow and phosphorus concentration in these streams, large fractions of the total phosphorus export occur in particulate form. Between 65% and 76% of the estimated total phosphorus load to the entire reservoir occurred in particulate form. Particulate phosphorus has less potential impact on reservoir eutrophication than dissolved phosphorus because of its relatively high sedimentation rate and low bioavailability. The following definition of "available phosphorus" has been shown to be useful for modeling reservoir responses to phosphorus loadings in various forms (Walker, 1985);

$$P_{ia} = 1.93\ P_{io} + .33\ P_{it} = 2.26\ P_{io} + .33\ (P_{it} - P_{io})$$

where,

P_{ia} = Inflow Available Phosphorus (ppb)

P_{io} = Inflow Ortho Phosphorus (ppb)

P_{it} =Inflow Total Phosphorus (ppb)

Lack of ortho phosphorus measurements for these streams precludes direct application of the above equation. Assuming that ortho phosphorus in surface runoff averages 79% of total dissolved phosphorus (Ahern et al.,1980; Bowman et al., 1979) available phosphorus can be expressed in terms of total and dissolved phosphorus measurements:

$$P_{io} = .79\ P_{id}$$

$$P_{ia} = 1.52\ P_{id} + .33\ P_{it} = 1.85\ P_{id} + .33\ (\ P_{it} - P_{id}\ )$$

where,

P_{id} = Inflow Total Dissolved Phosphorus (ppb)

This equation indicates that dissolved phosphorus loadings have approximately 5.6 (= 1.85/.33) times the impact of particulate phosphorus loadings on reservoir eutrophication. For this reason, predictions of reservoir response are much more sensitive to the measured dissolved phosphorus load.

Error CV's for load to the entire reservoir range from .06 to .11 for total phosphorus, .12 to .47 for dissolved phosphorus, and .09 to .17 for available phosphorus (Table 17). The relatively high CV's for dissolved phosphorus primarily reflect lower sampling frequency (averaging 28% of the total phosphorus sampling frequency at each station). A greater emphasis on monitoring dissolved phosphorus (or, preferably, ortho phosphorus) would increase the utility of the watershed monitoring data for predicting reservoir responses. Ortho phosphorus measurements would be preferable to total dissolved phosphorus. If a transition to ortho phosphorus measurements is feasible, both ortho and total dissolved phosphorus should be measured for at least a year to develop a statistical relationship between these two parameters (i.e., calibration of the ortho P/dissolved P ratio). This will permit refinement of historical available phosphorus loading estimates (Table 17).

4.2 Reservoir Response Model

The model formulations have been developed and tested against nationwide reservoir data sets (Walker,1985;1987). The **BATHTUB** program (Walker,1987) has been developed to facilitate model application to segmented reservoirs. Since spatial variations in Loch Raven are relatively small, a one-segment representation is adequate for preliminary modeling purposes. A spreadsheet version of **BATHTUB**, **CNET.WK1**, has been developed for modeling of one-segment, phosphorus-limited systems and is described in Appendix B.

Model inputs and outputs are listed in Tables 18 and 19, respectively. Each column of the worksheet represents a separate case, one per year for 1983 through 1987. The model is driven by estimates of runoff, inflow total phosphorus concentration, and inflow dissolved phosphorus developed for each year in Table 17. Additional input information include assumed atmospheric loading rates (Walker, 1985), reservoir morphometry (surface area, mean depth, Stack and Gottfredson, 1980), and observed water quality (intake station and reservoir means). Precipitation and evaporation statistics are ignored in this application because they are insignificant in relation to watershed inflows.

The model has been calibrated to the reservoir data set by adjusting the effective sedimentation coefficient for available phosphorus ("P Decay Calibration" in Table 18) so that average residual (=log [observed/predicted] reservoir-mean phosphorus) across years is zero. The calibration factor (1.95) indicates that the actual rate of phosphorus sedimentation in Loch Raven Reservoir is about 1.95 times that predicted by the empirical phosphorus retention model which has been calibrated to nationwide data sets (BATHTUB P Sedimentation Model 1, Walker, 1987). Based upon extensive error analyses (Walker, 1985), the 95% confidence range for the calibration factor in the model development data set is from .5 to 2.0. This indicates that the rate of phosphorus sedimentation in Loch Raven is unusually high (approximately 97th percentile). Calibration of the model to predict the average intake phosphorus concentrations (slightly lower than reservoir means) would require a calibration factor of 3.2. Phosphorus loadings calculated using unit flows (vs. daily flows) would probably be higher by ~25%, based upon results for Piney Run. This would require further increases in the calibration factor.

The high phosphorus sedimentation rate is not surprising in view of the fact that the slopes of the total phosphorus vs. flow regressions in watershed streams are also unusually high. Most of the particulate

Table 18
Reservoir Load/Response Model Inputs

CNET.WK1 VERSION 1.0		LOCH RAVEN RESERVOIR - APRIL-SEPTEMBER				
VARIABLE	UNITS	1983	1984	1985	1986	1987
WATERSHED CHARACTERISTICS...						
Drainage Area	km2	770.9	770.9	770.9	770.9	770.9
Precipitation	m/yr	0	0	0	0	0
Evaporation	m/yr	0	0	0	0	0
Unit Runoff	m/yr	0.466	0.572	0.253	0.294	0.311
Stream Total P Conc.	ppb	228.4	212.4	95.2	77.8	157.5
Stream Dissolved P Conc.	ppb	55.4	51.3	33.9	24.4	43.7
Stream Ortho P Conc.	ppb	43.8	40.5	26.8	19.3	34.5
Atmospheric P Load	kg/km2-yr	30	30	30	30	30
Atmospheric Ortho P Load	kg/km2-yr	15	15	15	15	15
POINT SOURCE CHARACTERISTICS...						
Flow	hm3/yr	0	0	0	0	0
Total P Conc	ppb	0	0	0	0	0
Ortho P Conc	ppb	0	0	0	0	0
RESERVOIR CHARACTERISTICS...						
Surface Area	km2	9.1	9.1	9.1	9.1	9.1
Mean Depth	m	8.46	8.46	8.46	8.46	8.46
Non-Algal Turbidity	1/m	0.08	0.08	0.08	0.08	0.08
Mean Depth of Mixed Layer	m	5	5	5	5	5
Mean Depth of Hypolimnion	m					
Observed Phosphorus - Dam	ppb	42	28.7	17	25.8	36.5
Observed Chlorophyll-a - Dam	ppb			5.6	9.7	8.7
Observed Secchi - Dam	meters		3.19	4.49	4.37	3.78
Observed Phosphorus - Mean	ppb		36.6	21.7	25.1	51.8
Observed Chl-a - Mean	ppb			6	7.7	9.5
Observed Secchi - Mean	meters		2.99	3.59	3.8	3.3
MODEL PARAMETERS...						
BATHTUB Total P Model Number	(1-8)	1	1	1	1	1
BATHTUB Total P Model Name		AVAIL P	AVAIL P	AVAIL P	AVAIL P	AVAIL P
BATHTUB Chl-a Model Number	(2,4,5)	4	4	4	4	4
BATHTUB Chl-a Model Name		P-LIN	P-LIN	P-LIN	P-LIN	P-LIN
Beta = 1/S vs. C Slope	m2/mg	0.025	0.025	0.025	0.025	0.025
P Decay Calibration		1.95	1.95	1.95	1.95	1.95
Chlorophyll-a Calibration		0.97	0.97	0.97	0.97	0.97
Chla Temporal Coef. of Var.		0.57	0.57	0.57	0.57	0.57
Chla Nuisance Criterion	ppb	20	20	20	20	20

Table 19
Reservoir Load/Response Model Outputs

CNET.WK1 VERSION 1.0		LOCH RAVEN RESERVOIR - APRIL-SEPTEMBER					
VARIABLE	**UNITS**	**1983**	**1984**	**1985**	**1986**	**1987**	
WATER BALANCE...							
Precipitation Flow	hm3/yr	0.00	0.00	0.00	0.00	0.00	
NonPoint Flow	hm3/yr	359.24	440.95	195.04	226.64	239.75	
Point Flow	hm3/yr	0.00	0.00	0.00	0.00	0.00	
Total Inflow	hm3/yr	359.24	440.95	195.04	226.64	239.75	
Evaporation	hm3/yr	0.00	0.00	0.00	0.00	0.00	
Outflow	hm3/yr	359.24	440.95	195.04	226.64	239.75	
AVAILABLE P BALANCE...							
Precipitation Load	kg/yr	354	354	354	354	354	
NonPoint Load	kg/yr	57421	65398	16208	14251	28435	
Point Load	kg/yr	0	0	0	0	0	
Total Load	kg/yr	57774	65751	16562	14604	28789	
Sedimentation	kg/yr	41105	44876	11330	9258	20461	
Outflow	kg/yr	16670	20875	5231	5346	8328	
PREDICTION SUMMARY...							
P Retention Coefficient	-	0.711	0.683	0.684	0.634	0.711	
Mean Phosphorus	ppb	46.4	47.3	26.8	23.6	34.7	
Mean Chlorophyll-a	ppb	12.6	12.9	7.3	6.4	9.4	
Algal Nuisance Frequency	%	13.7	14.5	2.0	1.1	5.4	
Mean Secchi Depth	meters	2.53	2.49	3.81	4.16	3.17	
Hypol. Oxygen Depletion A	mg/m2-d	852.0	860.6	647.8	607.5	737.2	
Hypol. Oxygen Depletion V	mg/m3-d	ERR	ERR	ERR	ERR	ERR	
Organic Nitrogen	ppb	450.4	456.2	329.1	309.1	378.1	
Particulate Phosphorus	ppb	20.2	20.7	10.8	9.2	14.6	
Chl-a x Secchi	mg/m2	31.9	32.0	27.8	26.7	29.9	
Carlson TSI P		59.5	59.8	51.6	49.8	55.4	
Carlson TSI Chl-a		55.5	55.7	50.1	48.8	52.6	
Carlson TSI Secchi		46.6	46.8	40.7	39.4	43.4	
OBSERVED / PREDICTED RATIOS...							
Phosphorus - Dam		0.91	0.61	0.63	1.09	1.05	
Chlorophyll-a - Dam		0.00	0.00	0.77	1.51	0.92	
Secchi - Dam		0.00	1.28	1.18	1.05	1.19	
Phosphorus - Mean		0.00	0.77	0.81	1.06	1.49	
Chlorophyll-a - Mean		0.00	0.00	0.82	1.20	1.01	
Secchi - Mean		0.00	1.20	0.94	0.91	1.04	
OBSERVED / PREDICTED T-STATISTICS...							**MEANS**
Phosphorus - Dam		-0.37	-1.84	-1.68	0.33	0.18	-0.75
Chlorophyll-a - Dam		ERR	ERR	-0.75	1.19	-0.23	0.07
Secchi - Dam		ERR	0.88	0.58	0.17	0.63	0.57
Phosphorus - Mean		ERR	-0.95	-0.78	0.23	1.47	-0.01
Chlorophyll-a - Mean		ERR	ERR	-0.55	0.53	0.02	-0.00
Secchi - Mean		ERR	0.65	-0.22	-0.33	0.15	0.06
TOTAL LOADS - ENGLISH UNITS...							
Total P	tons/yr	90.6	103.3	20.7	19.7	41.8	
Ortho P	tons/yr	11.6	13.2	3.9	3.3	6.2	
Available P	tons/yr	63.6	72.3	18.2	16.1	31.7	

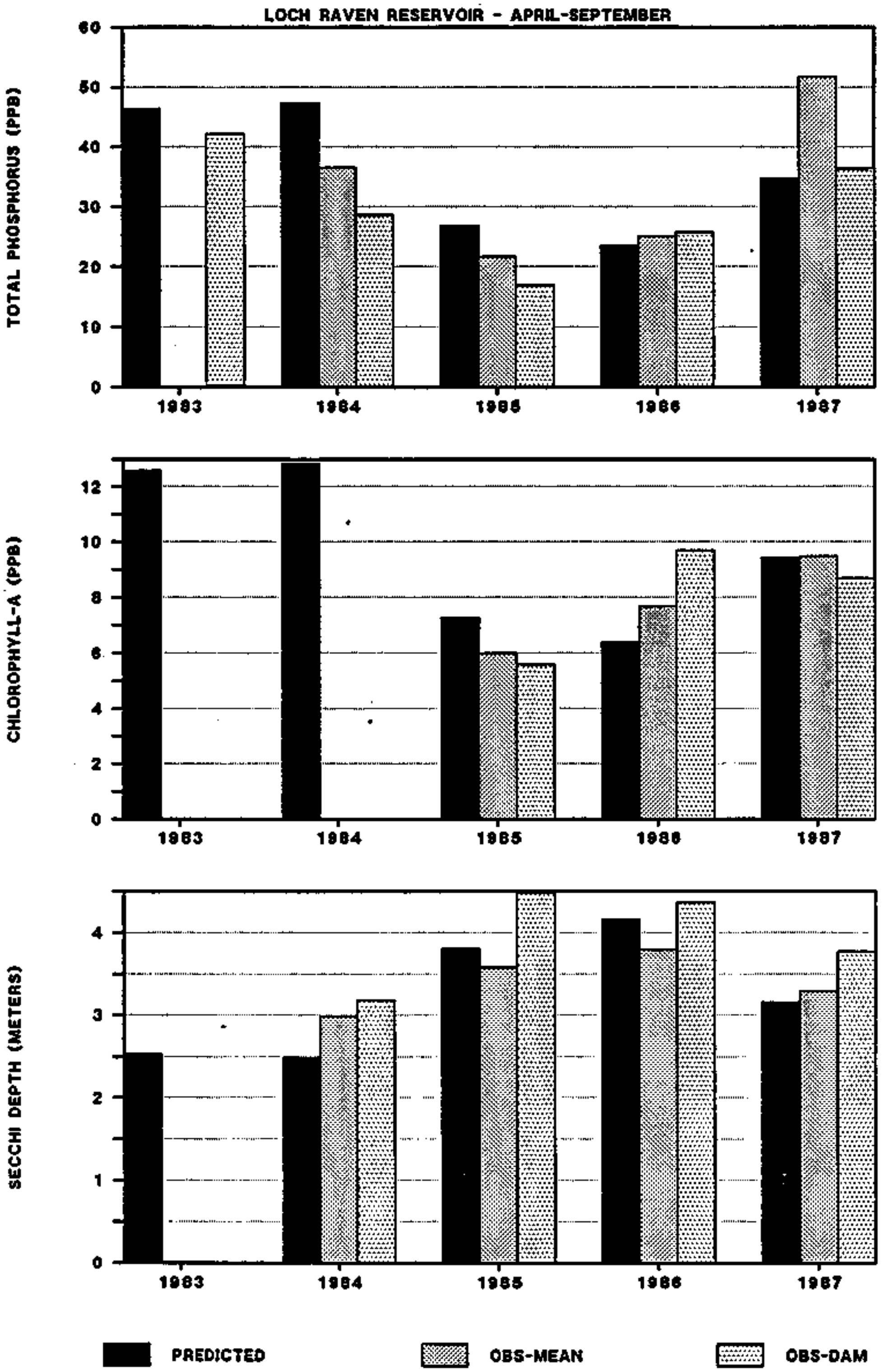
phosphorus exported from the watershed apparently requires high flow velocities to remain in suspension. These loadings would be relatively susceptible to sedimentation in the reservoir pool. Uncertainty regarding the stream ortho p/dissolved p ratio (.79 assumed) may also contribute to the unusually high sedimentation rate. Assuming a lower ratio would reduce the calibration factor.

Research on Corps of Engineer Reservoirs has lead to the development of chlorophyll-a models which consider effects of phosphorus, nitrogen, turbidity, and flushing rate on biological responses (Walker, 1985; 1987). The presence of significant nitrate nitrogen levels in Loch Raven throughout the summer indicates that nitrogen limitation is not a factor. Based upon observed mean chlorophyll-a concentrations and transparencies during the growing season, non-algal turbidities (~<.08 m^{-1}) are well below the range in which light limitation of algal growth starts to become important (~> .4 m^{-1}). Similarly, hydraulic residence times (.17 to .39 years for 1983-1987) exceed the level at which flushing rate normally limits chlorophyll-a production (~< .04 years), although flushing rate may limit algal production in Loch Raven on short-term basis. These characteristics of Loch Raven permit use of the simplest chlorophyll-a model, which predicts chlorophyll-a in direct proportion to the seasonal mean phosphorus concentration (Chl-a = .28 k_c Total P, BATHTUB Model 3, Walker, 1987).

The chlorophyll-a model has been calibrated to Loch Raven by adjusting the calibration factor (k_c, normally 1.0) so that average residual (=log [observed/predicted] reservoir-mean chlorophyll-a) across years is zero. The resulting calibration factor (.97) is very close to 1.0, which indicates that the observed reservoir chlorophyll-a levels are not significantly different from the average values predicted by the model.

Observed and predicted year-to-year variations in phosphorus, chlorophyll-a, and transparency are shown in Figure 23. Both the observations and predictions indicate that the reservoir nutrient and productivity levels are higher during years of higher runoff (1983, 1984,

Figure 23
Observed and Predicted Trophic State Indicators in Loch Raven Reservoir



1987), as compared with years of lower runoff (1985-1986). This primarily reflects the strong flow/concentration relationships characteristic of watershed streams, which cause higher inflow phosphorus concentrations in years of higher runoff. Overall, agreement between observed and predicted values is relatively good, especially when statistical confidence ranges for the observed values (Figure 14) are considered. Mean-squared t-statistics (calculated from t-values for individual years listed in Table 19) are .94, .19, and .15 for phosphorus, chlorophyll-a, and transparency, respectively. This means that error variances for Loch Raven are 94%, 19%, and 15%, respectively, of the error variances measured in the model-development data set.

4.3 Discussion

The model predicts a ~2-fold range (23.6 to 47.3 ppb) in reservoir mean total phosphorus concentrations for the five simulated years, as compared with an observed range of 22 to 52 ppb. This suggests that the observed scale of variations is similar to that predicted based upon year-to-year variations in hydrology.

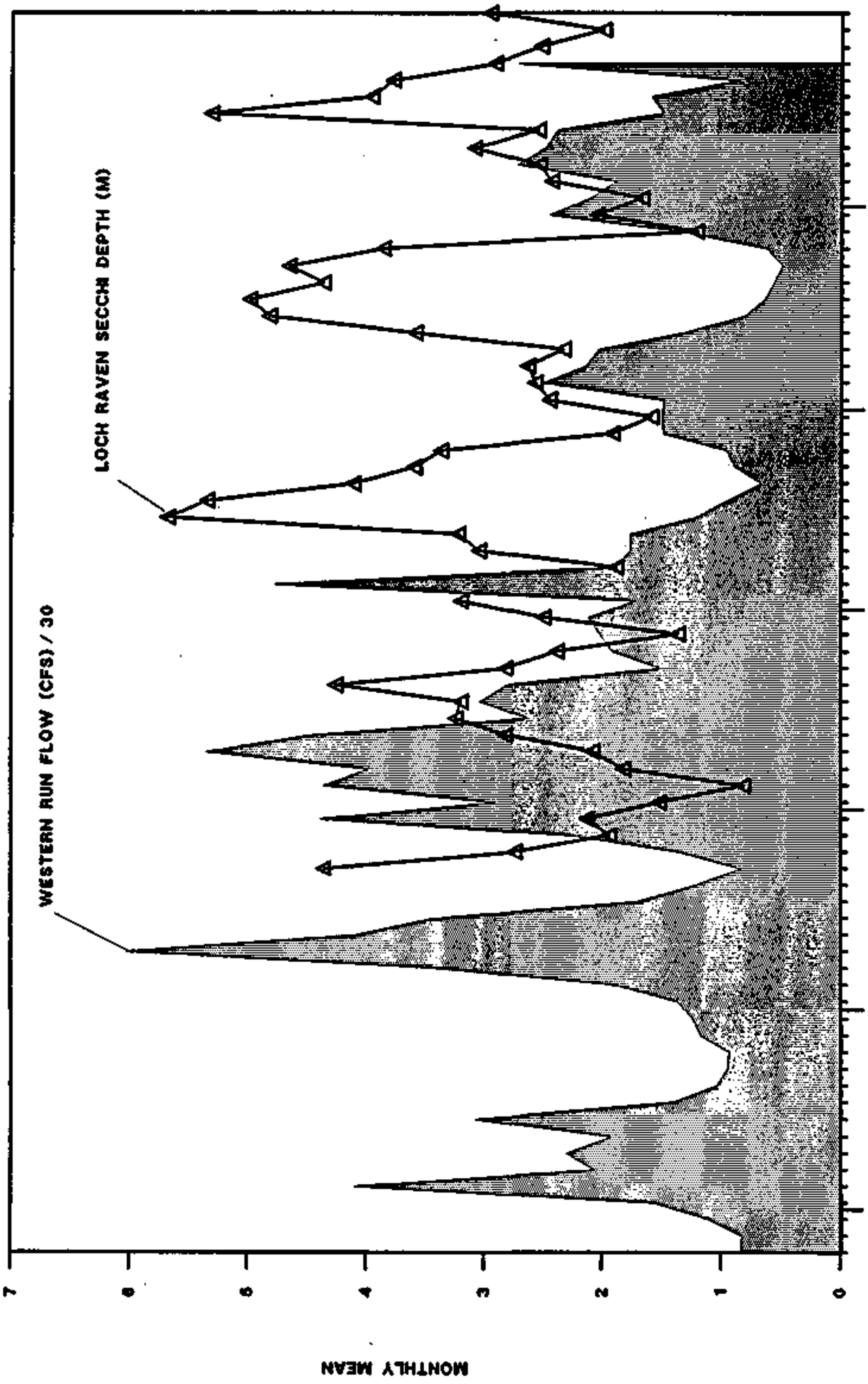
As indicated in Table 19, estimated total phosphorus loading rates to Loch Raven ranged from 20 to 103 tons/year for April-September of each year. The range of available phosphorus loading (more directly related to reservoir response) is 16 to 72 tons/yr. These ranges can compared with previous phosphorus loading estimated developed by Johns Hopkins University, 13 - 21 tons, and the Baltimore WQMO(1985), 56 tons for an average year. The JHU estimates are low because they are based upon limited data and back-calculation of loadings from observed reservoir phosphorus concentrations using an empirical phosphorus retention model. Such calculations would not reflect the unusually high phosphorus sedimentation rate in Loch Raven, as documented above.

Year-to-year variations in hydrology and loadings induce year-to-year variations in reservoir phosphorus and related water quality conditions. Calculation of the "longterm mean" based upon reservoir monitoring data is subject to the statistical limitations discussed above (see 3.4 **Reservoir Monitoring Program Design**). Even with precise estimates of seasonal means developed from intensive reservoir monitoring, calculation of the true "longterm mean" is difficult using only 4-5 years of direct monitoring data. Given a set of watershed responses, as reflected by flow/concentration relationships developed from historical data, it would be possible to use the reservoir load/response model to expand the effective period of record by simulating longterm hydrologic time series. Such an exercise would provide improved perspectives on the expected ranges of loadings and reservoir responses over longer time frames. Extrapolation of the observed hydrologic record at watershed monitoring stations could be based upon correlations with other, longterm gauges in the region with similar watersheds.

Development of load/response models using shorter time steps (e.g., monthly vs. seasonal) is an alternative method for increasing resolution for detecting reservoir changes over time (Montgomery and Reckhow, 1984). Figure 24 shows the monthly hydrograph for Western Run (shaded) in relation to the monthly mean Secchi depth at Loch Raven intake. A remarkable inverse correlation between these two variables is evident. The hydrograph is a relative indicator of natural driving forces and the Secchi depth is a relative indicator of reservoir responses (sensitive both to inorganic suspended solids contributed by reservoir tributaries and to algal growth occurring within the reservoir in response to phosphorus discharged from the watershed). Transparency is related both to the magnitude of flow and to the rate of change: lower during rising flows (streambed scour) and higher during falling flows.

A monthly time-series model for transparency driven by flow, season, and other related factors would provide a useful baseline for real-time tracking of the net watershed/reservoir response to hydrologic variations. The resolution of such a model for detecting changes over time could be considerably higher than that achievable using the direct monitoring or seasonal modeling approaches evaluated above.

Figure 24
Monthly Time Series - Western Run Flow and Loch Raven Intake Secchi Depth



5.0 CONCLUSIONS

(1) Analyses of stream monitoring data from Piney Run, Western Run, Beaverdam Run, and Gunpowder Falls reveal relatively strong positive relationships between concentration and flow for total phosphorus and suspended solids. These stream responses reflect watershed land uses, geologic factors, topography, and high drainage densities. The relationships are important because they magnify the effects of hydrologic variations (both short- and long-term) on stream loads and reservoir responses. This, in turn, makes monitoring and trend detection more difficult.

(2) Because of the strong flow/concentration relationships, stream load calculations using daily flow records in place of 15-minute unit records underestimate total phosphorus and suspended solids loads by 25-40% for Piney Run stations. Load calculations for dissolved species are insensitive to flow averaging interval.

(3) Comparison of longterm average load estimates at Yohn's Farm before and after installation of an animal waste storage facility in December 1986 indicate statistically significant reductions in total phosphorus (27%), dissolved phosphorus (69%), and suspended solids (60%) loads. Decreases in ammonia loads were offset by increases in nitrate nitrogen loads, possibly because of nitrification and leaching of the nitrogen load applied to the watershed soils after installation of the waste storage facility.

(4) Comparison of longterm average nonpoint load estimates for Piney Run at Butler Road before and after September 1984 (corrected for loads from Hampstead WWTP) indicate statistically significant reductions in total phosphorus (32%), dissolved phosphorus (27%), and suspended solids (72%)

loads. Decreases in ammonia loads were offset by increases in nitrate nitrogen loads.

(5) Observed load reductions at Piney Run stations are consistent with the hypothesis that watershed management activities (agricultural BMP's) had measurable effects on nutrient and sediment loads which are of importance with respect to management of eutrophication and sedimentation in downstream Loch Raven Reservoir.

(6) Based upon monitoring frequencies and observed variability in the flow/concentration relationships, the minimum detectable percent reductions (MDR%) in longterm average total phosphorus loads are 28% for Yohn's Farm station and 24% for Piney Run at Butler Road. Figure 12 can be used to estimate MDR% as a function of monitoring frequency. Changes in total phosphorus loads exceeding ~50% are detectable for a modest number of sampled events per time period (~10), whereas detection of a 20% change would require more than 60 events, assuming that the distribution of events across flow regimes is similar to that characteristic of the historical data sets.

(7) Based upon April-September samples at Loch Raven Intake for the 1984-1987 period, average water quality conditions (Mean +/- 1 Standard Error of Mean) are as follows: Total Phosphorus (27 +/- 4 ppb), Chlorophyll-a (8 +/- 1.2 ppb), and Secchi Depth (4 +/- .3 meters). The phosphorus and chlorophyll-a levels suggest that Loch Raven is at the mesotrophic/eutrophic boundary. Year-to-year variations in the seasonal mean total phosphorus concentration ranged from 16 to 37 ppb, as compared with the target concentration of 26 ppb.

(8) Spatial variations within the reservoir reflect normal sedimentation patterns and hydrodynamic factors. Spatial variations are relatively minor because of the short hydraulic retention time of Loch Raven (ranging from .17 to .39 years

for April-September 1983-1987). Sampling of 3 stations (vs. 5) seems adequate to characterize the reservoir.

(9) Variance component analysis have been conducted to quantify within-year and among-year variations in Loch Raven monitoring data. Results for chlorophyll-a and transparency are typical of other lake and reservoir data sets. Within-year standard deviations for total phosphorus are 2-3 times above typical values derived from other data sets and exceed the 98th percentile of values derived from Corps of Engineer reservoirs. The unusually high variance in the phosphorus data imposes severe limitations on the feasibility of detecting changes in reservoir conditions over time. Analysis of replicate samples and a thorough review of sampling procedures, laboratory procedures, and reporting procedures are recommended to define sources of this variance, so that steps can be taken to minimize them in future monitoring.

(10) A Lotus-123 worksheet, **LRSD.WK1**, has been developed to facilitate statistical evaluation of reservoir monitoring designs. Using monitoring frequencies and variance components calculated from Loch Raven 1984-1987 data, coefficients of variation for estimates of longterm means are .146 for total phosphorus, .153 for chlorophyll-a, and .086 for transparency. The probability of detecting a 28% change in the mean based upon comparison of two, 4-year periods of monitoring is 33% for total phosphorus, 30% for chlorophyll-a, and 65% for transparency. With phosphorus variance components typical of other reservoir sets, the probability of detecting a 28% change would increase from 33% to 80% for the same monitoring frequency.

(11) **LRSD.WK1** has been applied to evaluate alternative sampling designs for Loch Raven. Recommendations include reduction in spatial coverage from 5 to 3 stations, biweekly sampling, and further investigation of phosphorus variance components via

replicate sampling. The detection of changes in reservoir conditions in relation to the 26 ppb objective is limited more by the unusually high phosphorus variability than by spatial or temporal sampling frequencies.

(12) The linkage between watershed loads and reservoir responses is analyzed using a mass-balance model applied to data from April through September of 1983 through 1987. The model is implemented using **CNET.WK1**, a simplified version of **BATHTUB**, a model developed for simulating eutrophication responses in Corps of Engineer reservoirs (Walker, 1987).

(13) The calibrated phosphorus sedimentation coefficient in Loch Raven is 1.95 times the value estimated by the empirical sedimentation model developed from nationwide reservoir data sets. The unusually high sedimentation coefficient is consistent with the unusually high concentration/flow slope measured in tributary streams. Particles transported to the reservoir under high-flow conditions apparently require high velocities to stay in suspension and are thus relatively susceptible to sedimentation in the reservoir pool.

(14) Additional emphasis on monitoring of dissolved (and/or ortho) phosphorus at stream stations is recommended to provide load estimates which are more meaningful than total phosphorus with respect to reservoir biological response.

(15) Based upon mass-balances constructed for 5 separate years, the 2.3-fold range in average runoff (.25 to .57 m/yr) was accompanied by a 5.2-fold range in total phosphorus load (20 to 104 tons/yr) and a 4.5-fold range in available phosphorus load (16 to 72 tons/year). These variations reflect year-to-year variations in flow frequency distributions at each monitoring station.

(16) Agreement between observed and predicted year-to-year variations in phosphorus, chlorophyll-a, and transparency is generally good. Error variances are below those typical of nationwide data sets used in development of the empirical models. The model predicts a 24 to 47 ppb range in reservoir-mean total phosphorus concentrations for the five simulated years, as compared with the observed range of 22 to 52 ppb.

(17) Refinements to the reservoir load/response modeling should involve the following:

(a) consideration of possible year-to-year variations in flow/concentration relationships in calculating loads for each station and year. This will stress the historical data base, because of the limited number of samples within each year. Modifications to the FLUX program (e.g., use of time-dependent weighting functions) to facilitate calculation of yearly loads from sparse data sets are being considered.

(b) estimation of watershed loads using 15-minute unit flows in place of daily flows;

(c) development of a segmented version of the model which simulates spatial variations in Loch Raven;

(d) refinements in the estimated ortho P/dissolved P ratio needed to calculate available P loads, based upon site-specific measurements;

(e) expansion of the model domain to simulate the entire watershed, including Prettyboy Reservoir;

(f) application of the stream and reservoir response models to longer hydrologic records to provide improved estimates of longterm means and ranges.

(18) The possibility of developing time-series models for tracking reservoir conditions in the presence of hydrologic variability is supported by the strong inverse relationship between monthly flow in Western Run and monthly mean transparency at Loch Raven Dam. Such "real-time" models may have considerably higher resolution for detecting changes than the seasonal models discussed above.

(19) With respect to overall program objectives, the Piney Run watershed data indicate that statistically significant reductions in phosphorus and sediment loads have resulted from implementation of agricultural Best Management Practices. This is consistent with the hypothesis that keeping cows and dirt out of a stream is good for downstream water quality. Results support continued and aggressive implementation of these practices, given (a) the known cause-effect relationships linking such loads to reservoir impairment and (b) the fact that the target phosphorus concentration (26 ppb) has apparently not been achieved for Loch Raven. The eventual demonstration of a percentage reduction in the longterm average reservoir phosphorus concentration in Loch Raven will be relatively difficult from a statistical point of view, especially given the high variability of the historical phosphorus data. Tracking of reservoir conditions in the future should be oriented towards comparing measurements with the fixed target concentration of 26 ppb, a much easier statistical problem than detecting changes.

(20) From a water-supply perspective, further evaluation of the 26 ppb target concentration is recommended, particularly with respect to the appropriate spatial scale (reservoir-mean vs. intake mean) and temporal scale (longterm mean vs. individual yearly means at a specified violation frequency). Correlations between phosphorus and algal nuisance frequencies (Walker, 1984) may be useful for refining reservoir phosphorus objectives.

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APPENDIX A

LRSD.WK1 - LAKE/RESERVOIR SAMPLING DESIGN WORKSHEET

Version 1.0 - December 1988

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LRSD.WK1 is a Lotus-123 worksheet which has been created to facilitate statistical evaluation of lake and reservoir sampling program designs. The assumed objective of the monitoring program is to estimate the longterm geometric mean concentration at a given station and/or to detect a step change in the longterm mean between two periods of monitoring. Samples would normally be taken from the epilimnion during the growing season for characterization of trophic state. The precision of the geometric mean is slightly higher than the precision of the arithmetic mean for variables which are lognormally distributed. For purposes of survey design, however, the distinction between the two is usually negligible (i.e., the coefficient of variation (CV) of the geometric mean ~ the CV of the arithmetic mean). The worksheet employs a modified version of the methodology described by Smeltzer et al. (1988) for estimating the precision of longterm means calculated from lake survey data.

The sampling program design is specified by the number of years of baseline monitoring, season length (days per year), and sampling interval (days between samples, e.g., 7 for weekly sampling). Precision in the longterm geometric mean is calculated from within-year and among-year variance components (Walker, 1980, Knowlton et al., 1984). Variance components, expressed as standard deviations on a base-e logarithmic scale, can be estimated from prior monitoring data for a particular station and water quality component using a one-way analysis of variance. Otherwise, literature values may be used for these parameters, as summarized by Smeltzer et al. (1988) for various lake and reservoir data sets (see **APPENDIX**).

The effects of serial correlation (date-to-date within a given year) on the precision of yearly and longterm means are considered using the "effective sample size" concept (Matalas and Langbein, 1962; Lettenmaier, 1976). Experience with several lake data sets suggests that autocorrelation can become important at high monitoring frequencies (e.g., weekly or more frequent). Autocorrelation reduces the effective number of samples for calculating the yearly mean. The program requires an estimate of the serial correlation coefficient for a 1-day sampling frequency. Values in the range of .78 to .87 were estimated by Lettenmaier (1976) from 7 intensive data sets. Year-to-year variations in the mean are assumed to be serially independent.

Equations used for calculating the variance of and confidence factors for the geometric mean calculated for a given set of variance components, autocorrelation coefficient, and survey design are given below:

$S_m{}^2 = S_y{}^2/N_y + S_d{}^2/N_yN_{de}$ = variance of longterm log$_e$-mean

N_{de} = FUNCTION(N_d,r,k) (Matalas and Langbein, 1962)

$CV = [\ S_m{}^2\ ]^{1/2}$ = coefficient of variation of geometric mean

$f_l = \exp(-\ t\ S_m)$ = lower confidence factor for geometric mean
prob [(true mean / estimated mean) > f_l] ~ 95%

$f_u = \exp(\ t\ S_m)$ = upper confidence factor for geometric mean
prob [(true mean / estimated mean) < f_u] ~ 95%

where,

k = sampling interval (days between samples)

t = t statistic with $N_y\ N_{de}$ -1 degrees of freedom, area of each tail = 5%

S_y = among-year standard deviation

N_y = number of monitoring years

S_d = within-year standard deviation

N_d = number of sampling dates per year

N_{de} = effective sampling dates per year

r = lag 1-day autocorrelation coefficient

The t-test (Montgomery and Loftis, 1987) is employed to test for a significant difference in the longterm geometric mean calculated using data from two separate time periods. The test is applied to log-transformed data and the null hypothesis is that the means of the logarithms are not significantly different:

$$t = (m_2 - m_1)\ /\ S_{2-1}$$

$$S_{2-1} = (S^2_{m,1} + S^2_{m,2})^{1/2}$$

$$\text{dof} = N_{y,1}\ N_{de,1} + N_{y,2}\ N_{de,2} - 2$$

Null Hypothesis : $m_1 = m_2$ is accepted if $|t| < t_{a,dof}$

where,

$1,2$ = subscripts denoting first and second time periods, respectively

S_{2-1} = standard error of difference in log means between periods 1 and 2

m_i = log-mean for period i   dof = degrees of freedom

a = significance level

LRSD.WK1 estimates two statistics relevant to detection of a step change with a t-test:

(1) **"Minimum Detectable Change (MDC%)"** is defined by Spooner et al. (1987):

$$t = t_{a,dof}$$

$$|m_2 - m_1| = t_{a,dof}\, S_{2-1}$$

$$MDC\% = 100\ [1 - \exp(-|m_2 - m_1|)] = 100\ [1 - \exp(-\, t_{a,dof}\, S_{2-1})\ ]$$

The **MDC%** equals the minimum estimated percent change in the geometric mean which could cause rejection of the null hypothesis, given the error variances of the log-means calculated for lake sampling frequencies during each time period.

(2) The **"Power%"** of the t-test is computed using equations derived from Lettenmaier (1976):

$$N_T = \log_e(1 + C\%/100)\ /\ S_{2-1} \qquad = \text{dimensionless trend number}$$

$$Power\% = 100\ F(N_T - t_{a,dof}, dof)$$

where,

C% = hypothetical step change in geometric mean (%)

F = cumulative frequency distribution of t

This statistic equals the probability of detecting a specified percent change in the geometric mean (i.e., probability that null hypothesis would be rejected if the specified change of magnitude C% actually occurred), given the error variances of the log-means calculated from lake sampling frequencies during each time period.

Both of **MDC%** and **Power%** statistics are sensitive to sampling interval and duration. The specified within-year and among-year variance components are assumed to apply to both time periods. The assumed significance level (a) for both statistics is 5% for a one-tailed t-test (~appropriate for detecting a change in a known direction) and 10% for a two-tailed t-test (~appropriate for detecting a change in an unknown direction). If this is confusing, welcome to the club.

Worksheet organization is illustrated in Table 1. Each column represents a separate case. This facilitates comparison of alternative sampling program designs. The original worksheet permits evaluation of six cases (columns) simultaneously. Additional columns may be added as required, using the Lotus copy command (make sure to copy entire column, rows 1-430).

The following information is entered by the user for each case or column:

Case Label	for labeling graphs
Within-Year Ln Std Deviation	estimated from lake data and/or literature
Among-Year Ln Std Deviation	"
Lag 1-Day Auto-Correlation Coef.	"
Number of Years (N)	duration of baseline monitoring
Sampling Duration	days per year, e.g., growing season length
Sampling Interval	days between samples within each year
Hypoth. Change in Longterm Mean C%	for power computations

Program outputs specific for each column include:

POWER % = Probability of detecting a C% change which occurs in the longterm geometric mean, given N years of monitoring before and after the change

MDC% = Minimum detectable change in longterm geometric mean, given N years of sampling before the change and N years of sampling after the change

CV(Longterm Mean) = Expected coefficient of variation of longterm geometric mean computed from N years of data

CV(Yearly Mean) = Expected coefficient of variation of the geometric mean for each year of data

95% Confidence Factors - Low & High = Lower and upper 95% confidence limits for ratio of true geometric mean to measured geometric mean (f_l and f_u above)

Sample Saturation % = Effective sample size per year / maximum possible sample size, based upon autocorrelation effects (Lettenmaier, 1976)

Sensitivity analysis tables include:

mdc% vs. years of monitoring for N years of baseline data
minimum detectable change in longterm geometric mean for a fixed number years of baseline data (N) and variable years of post-baseline data (1 to 100)

cv (longterm mean) % vs. years of monitoring
coefficient of variation of longterm geometric mean for variable number of years of monitoring (1 to 100)

power % vs. step change % for N years of monitoring before and after
probability of detecting step changes in the range of 10 to 100% based upon N years of monitoring before the change and N years after the change

power % vs. years of monitoring for N yrs of baseline data and change C%
probability of detecting a fixed step change of C% based upon N years of data before the change and variable number of years (1-100) after the change.

Graphic outputs include 5 named graphs, as illustrated in Figures 1-5. To display each graph in sequence, invoke the '\g' macro by pressing 'ALT' and 'g' simultaneously. Because of a Lotus-123 quirk, only portions of the graph legends (range labels) appear on the printed figures; screen images are complete.

The example shown in Table 1 and Figures 1-5 illustrates sensitivity to sampling interval (cases = annual, bimonthly, monthly, biweekly, weekly, semiweekly) using variance components which are typical for total phosphorus and a 3-year baseline monitoring period (N).

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Table 1
LRSD Worksheet

```
LAKE/RESERVOIR SAMPLING DESIGN      LRSD-1.0     W. WALKER        DEC 1988
Press 'ALT-G' for graphs

INPUTS....................       SENSITIVITY TO SAMPLING INTERVAL - TOTAL P
case labels ------------->      ANNUAL BIMONTHLY MONTHLY BIWEEKLY   WEEKLY SEMIWEEKLY
among-year ln std dev             0.12      0.12      0.12      0.12      0.12      0.12
within-year ln std dev             0.3       0.3       0.3       0.3       0.3       0.3
lag 1-day auto-correlation         0.8       0.8       0.8       0.8       0.8       0.8
sampling duration = N (yrs)          4         4         4         4         4         4
sampling season (days/year)        180       180       180       180       180       180
sampling interval (days)           180        60        30        14         7         4
hypothet. step change C (%)         25        25        25        25        25        25

OUTPUTS..................
power for detecting C %           18.7      41.1      56.6      67.6      72.0      73.2
minimum detectable change %       35.9      22.6      18.4      16.0      15.1      14.9
cv (longterm geom. mean ) %       16.2      10.5       8.6       7.4       7.0       6.9
cv ( yearly geom. mean ) %        30.0      17.3      12.3       8.7       7.3       6.8
95% confid. factor - low         0.684     0.828     0.863     0.883     0.890     0.891
95% confid. factor - high        1.463     1.208     1.158     1.133     1.124     1.122
sample saturation %                4.9      14.6      29.1      57.6      83.0      93.6
total samples per season           1.0       3.0       6.0      12.9      25.7      45.0
total samples per N years          4.0      12.0      24.0      51.4     102.9     180.0

mdc% vs. years of monitoring for N years of baseline data
                             1    50.4      33.3      27.5      24.1      22.9      22.5
                             2    41.9      26.9      22.1      19.2      18.2      18.0
                             3    38.1      24.1      19.7      17.2      16.3      16.0
                             4    35.9      22.6      18.4      16.0      15.1      14.9
                             5    34.4      21.6      17.6      15.2      14.4      14.2
                             6    33.3      20.8      17.0      14.7      13.9      13.7
                             7    32.5      20.3      16.5      14.3      13.5      13.3
                             8    31.9      19.9      16.2      14.0      13.3      13.1
                             9    31.4      19.5      15.9      13.8      13.0      12.8
                            10    31.0      19.3      15.7      13.6      12.8      12.6
                           100    27.4      16.8      13.7      11.8      11.2      11.0

cv (longterm geometric mean) % vs. years of monitoring
                             1    32.3      21.1      17.2      14.8      14.0      13.8
                             2    22.8      14.9      12.1      10.5       9.9       9.8
                             3    18.7      12.2       9.9       8.6       8.1       8.0
                             4    16.2      10.5       8.6       7.4       7.0       6.9
                             5    14.4       9.4       7.7       6.6       6.3       6.2
                             6    13.2       8.6       7.0       6.1       5.7       5.6
                             7    12.2       8.0       6.5       5.6       5.3       5.2
                             8    11.4       7.4       6.1       5.2       5.0       4.9
                             9    10.8       7.0       5.7       4.9       4.7       4.6
                            10    10.2       6.7       5.4       4.7       4.4       4.4
                           100     3.2       2.1       1.7       1.5       1.4       1.4

power % vs. step change % for N years of monitoring before and after
                            10     8.8      14.7      19.0      23.0      25.2      25.3
                            20    14.8      31.6      42.8      53.2      57.5      58.7
                            30    23.1      51.8      68.2      79.6      83.7      84.8
                            40    32.8      70.0      86.1      93.9      96.0      96.4
                            50    43.3      83.6      95.0      98.6      99.2      99.3
                            60    54.5      91.9      98.4      99.7      99.9      99.9
                            70    64.2      96.2      99.5      99.9     100.0     100.0
                            80    72.2      98.3      99.8     100.0     100.0     100.0
                            90    78.8      99.2      99.9     100.0     100.0     100.0
                           100    84.1      99.6     100.0     100.0     100.0     100.0

power % vs. years of monitoring for N yrs of baseline data and change C%
                             1     9.0      20.6      29.6      37.1      40.4      41.5
                             2    12.6      28.7      41.3      52.5      57.3      58.7
                             3    15.9      34.1      49.3      61.6      66.2      67.5
                             4    18.7      37.8      55.0      67.1      71.8      73.2
                             5    21.0      40.7      59.0      71.0      75.7      77.1
                             6    22.9      43.0      61.7      73.9      78.6      79.9
                             7    24.4      45.0      63.8      76.0      80.7      82.0
                             8    25.7      46.7      65.5      77.8      82.4      83.6
                             9    26.8      48.0      66.9      79.2      83.6      84.9
                            10    27.8      49.0      68.0      80.3      84.7      85.9
                           100    37.9      60.4      79.1      89.7      92.8      93.6
```

Figure 1
Named Graph: BAR

This graph shows the following values for each of six working columns in the spreadsheet:

POWER% = probability of detecting a change of C% based upon N years of monitoring before and after change.

MDC % = minimum detectable change in longterm mean for N years of monitoring before and after change.

CV(MEAN) = coefficient of variation of longterm geometric mean based upon N years of monitoring

CV(YEARLY MEAN) = coefficient of variation of geometric mean for individual year

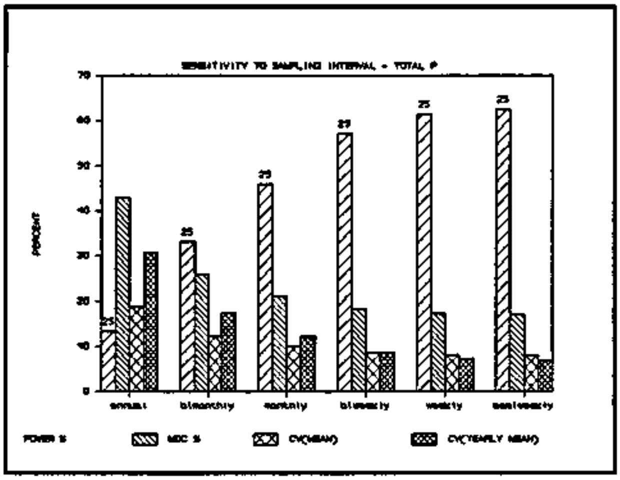


Figure 2
Named Graph: CVMEAN

X-Axis = X years of monitoring

Y-Axis = coefficient of variation of longterm geometric mean calculated from X years of data

Each line represents a separate column in the worksheet.

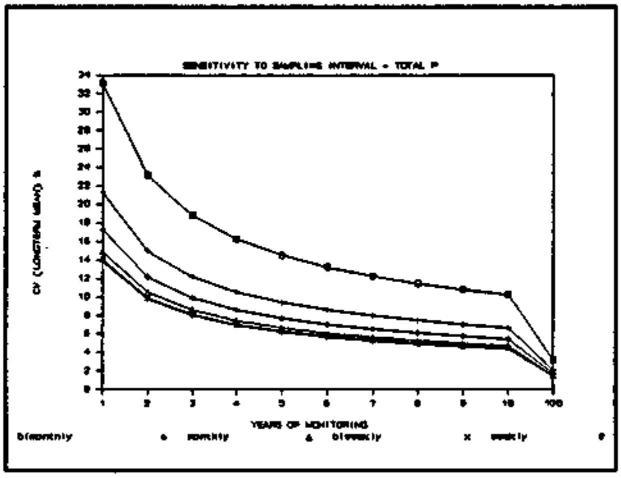


Figure 3
Named Graph: MDC

X-Axis = X years of monitoring after N years of baseline monitoring

Y-Axis = minimum detectable change in longterm mean, based upon comparison of N years of baseline data with X years of data collected after the change.

Each line represents a separate column in the worksheet.

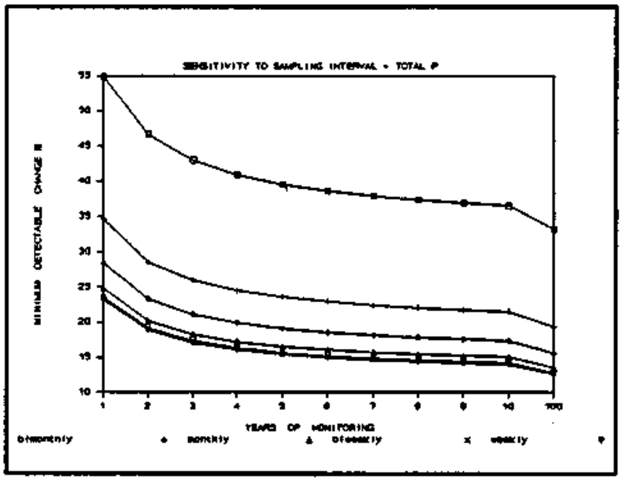


Figure 4
Named Graph: POWER

X-Axis = Actual Change in Longterm Mean (%)

Y-Axis = Probability of Detecting Change, based upon N years of monitoring before change and N years of monitoring after change.

Each line represents a separate column in the worksheet.

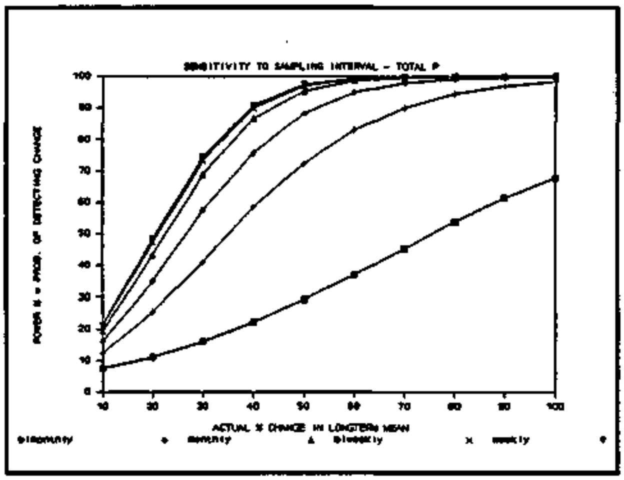
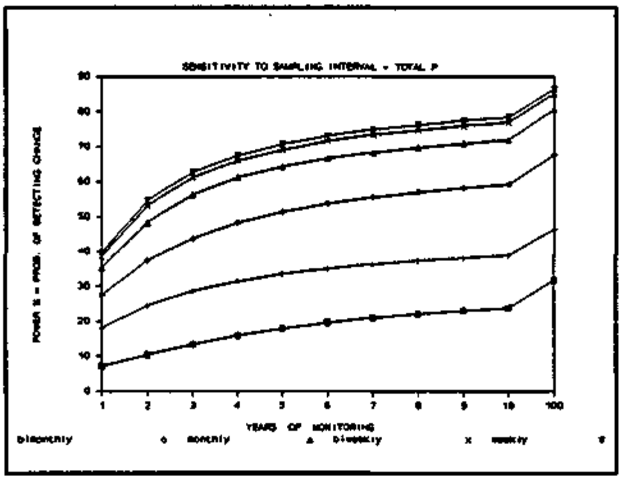


Figure 5
Named Graph: POWERT

X-Axis = X Years of Monitoring after N years of Baseline Monitoring

Y-Axis = Probability of detecting a fixed percent change (C%), based upon comparison of N years of baseline data with X years of data collected after the change.

Each line represents a separate column in the worksheet.



APPENDIX- LRSD 1.0

Computation of Variance Components from Lake Survey Data (Modified from Smeltzer et al, 1988)

The following procedure is designed for application to data from one lake station monitored for N_y years at an average of N_d sampling dates per year, within appropriate depth and seasonal strata (e.g., mixed layer, summer or growing season). A total of 20 observations over a 3-year period is recommended as a minimal basis for estimating station-specific variance components to be used in survey design calculations; otherwise, greater weight should be given to literature values (see figures below from Smelter et al.,1988; also, Knowlton et al., 1984).

1. Calculate means (or medians) of samples by sampling date. If the sampling design includes at least three observations per date (e.g., replicates or multiple sample depths within the mixed layer), taking medians provides a degree of protection against errant observations.

2. Transform the daily summary values to natural logarithms. Set any "zero" values equal to the lower detection limit before transforming.

N_t = total number of sampling dates

N_y = total number of years

n_i = number of observations for year i

N_d = average (n_i) = N_t/N_y

3. Conduct a one-way analysis of variance (Snedecor and Cochran, 1967) with groups defined based upon sampling year. The ANOVA yields the following mean square statistics:

$M_y{}^2$ = mean squared deviation among years

$M_d{}^2$ = mean squared deviation within years

4. Estimate among-year and within-year standard deviations:

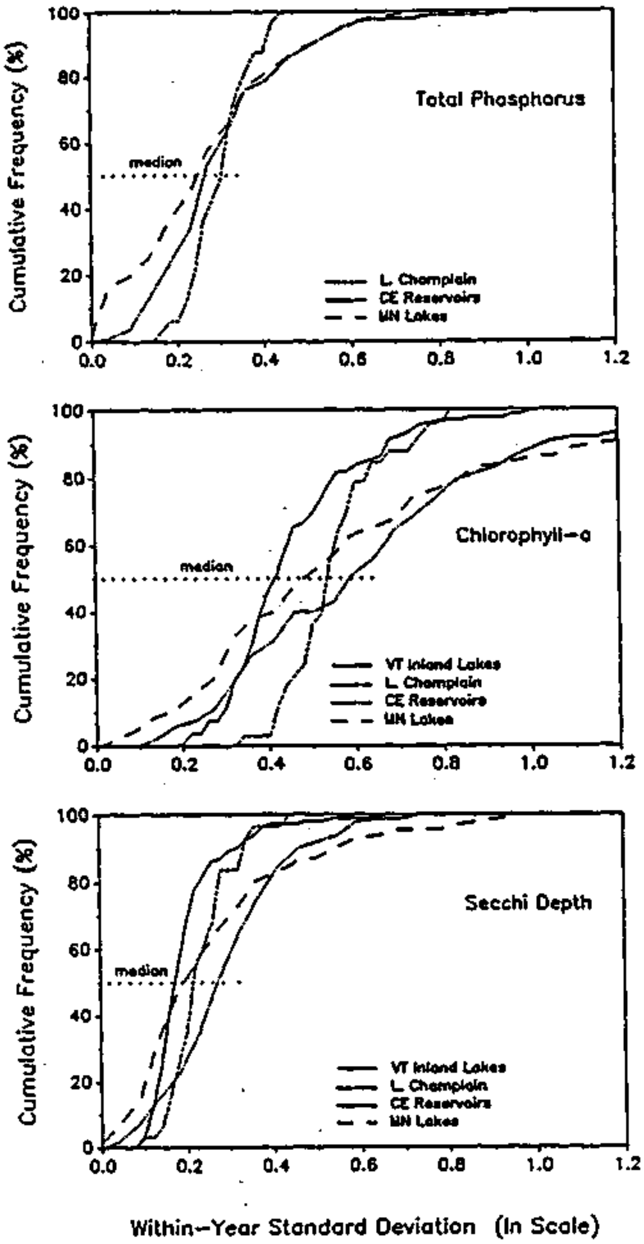
$S_y = [\ (M_y{}^2 - M_d{}^2)\ /\ N_0\ ]^{1/2}$ = year-to-year standard deviation of ln(conc)

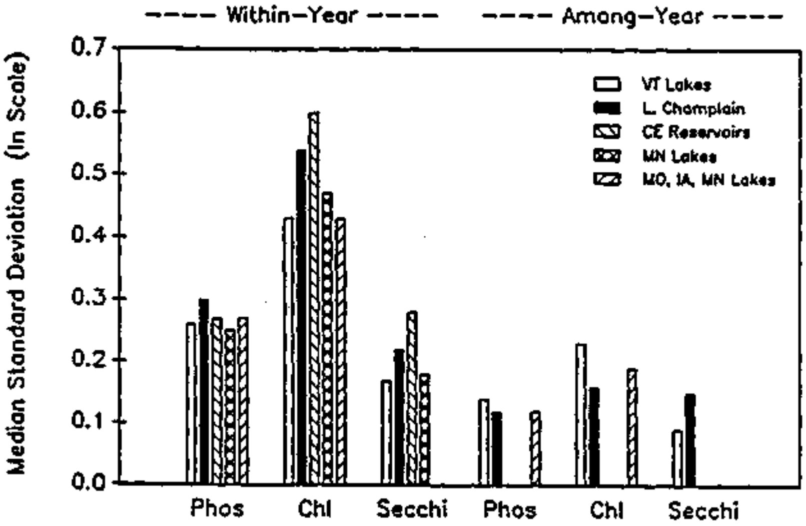
$N_0 = (N_t - \mathrm{SUM}_i(n_i{}^2)/N_t)/(N_y - 1)$ = adjusted samples per year ($\sim N_d$)

$S_d = [\ M_d{}^2\ ]^{1/2}$ = date-to-date standard deviation of ln(conc)

APPENDIX- LRSD 1.0

Lake Variance Component Distributions - Smeltzer et al.(1988)





APPENDIX B

CNET.WK1 - Reservoir Eutrophication Modeling Worksheet

Version 1.0 - November 1988

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CNET.WK1 is a Lotus-123 worksheet which implements empirical models for predicting eutrophication and related water quality conditions in reservoirs and lakes. The worksheet is a condensed and simplified version of **BATHTUB**, a program developed for the U.S. Army Corps of Engineers (Walker, 1987). The models estimate reservoir eutrophication responses, as measured by phosphorus, chlorophyll-a, transparency, organic nitrogen, and hypolimnetic oxygen depletion, as a function of watershed runoff, inflow phosphorus concentrations, and reservoir morphometry. The formulation, calibration, and testing of the models based upon various reservoir and lake data sets are described in reports prepared for the Corps of Engineers (Walker, 1981,1982,1985,1987). **BATHTUB** documentation (Walker, 1987) summarizes the relevant equations and provides general guidance for using the model and interpreting the output. As distinct from **BATHTUB**, **CNET.WK1** applications are restricted to single-segment reservoirs in which nitrogen limitation of algal growth is not important (nitrogen balances are not formulated). Optional models for phosphorus sedimentation and chlorophyll-a are identical to those described in the **BATHTUB** documentation (Walker,1987, pp. IV-7 to IV-10).

The worksheet is organized in columns; each column (C-G in the following example) is a separate case. Additional columns may be added using the Lotus Copy command. Input cells (shown in green, Lotus unprotected cells) are located at the top of each column. Input, output, and calculation sections of the worksheet are shown in Tables 1, 2, and 3, respectively. In this example, each column contains data from a different year. Several named graphs are included to facilitate case comparisons.

REFERENCES

Walker, W.W., Jr., "Empirical Methods for Predicting Eutrophication in Impoundments - Report 1 Phase I: Data Base Development", prepared for Department of the Army, US Army Corps of Engineers, Washington DC, Technical Report E-81-9, Environmental Laboratory, USAE Waterways Experiment Station, Vicksburg, Mississippi, May 1981.

Walker, W.W., Jr., "Empirical Methods for Predicting Eutrophication in Impoundments - Report 2 Phase II: Model Testing", prepared for Department of the Army, US Army Corps of Engineers, Washington DC, Technical Report E-81-9, Environmental Laboratory, USAE Waterways Experiment Station, Vicksburg, Mississippi, September 1982.

Walker, W.W., "Statistical Bases for Mean Chlorophyll-a Criteria" in "Lake and Reservoir Management: Practical Applications", Proceeding of Fourth Annual Conference, North American Lake Management Society, pp. 57-62, 1984.

Walker, W.W., Jr., "Empirical Methods for Predicting Eutrophication in Impoundments - Report 3 Phase II: Model Refinements", prepared for Department of the Army, US Army Corps of Engineers, Washington DC, Technical Report E-81-9, Environmental Laboratory, USAE Waterways Experiment Station, Vicksburg, Mississippi, March 1985.

Walker, W.W., Jr., "Empirical Methods for Predicting Eutrophication in Impoundments -Report 4 Phase III: Applications Manual", prepared for Department of the Army, US Army Corps of Engineers, Washington DC, Technical Report E-81-9, Environmental Laboratory, USAE Waterways Experiment Station, Vicksburg, Mississippi, July 1987.

TABLE 1 - CNET.WK1 INPUT SECTION

Corps of Engineer Reservoir Model Network - P Limited Systems W. Walker

CNET.WK1 VERSION 1.0		LOCH RAVEN RESERVOIR - APRIL-SEPTEMBER					
VARIABLE	UNITS	1983	1984	1985	1986	1987	
PROBLEM TITLE ----------------------->		LOCH RAVEN RESERVOIR - APRIL-SEPTEMBER					
CASE LABELS ------------------------->		1983	1984	1985	1986	1987	
WATERSHED CHARACTERISTICS...							
Drainage Area	km2	770.9	770.9	770.9	770.9	770.9	
Precipitation	m/yr	0	0	0	0	0	
Evaporation	m/yr	0	0	0	0	0	
Unit Runoff	m/yr	0.466	0.572	0.253	0.294	0.311	
Stream Total P Conc.	ppb	228.4	212.4	95.2	77.8	157.5	
Stream Ortho P Conc.	ppb	43.8	40.5	26.8	19.3	34.5	
Atmospheric P Load	kg/km2-yr	30	30	30	30	30	
Atmospheric Ortho P Load	kg/km2-yr	15	15	15	15	15	
POINT SOURCE CHARACTERISTICS...							
Flow	hm3/yr	0	0	0	0	0	
Total P Conc	ppb	0	0	0	0	0	
Ortho P Conc	ppb	0	0	0	0	0	
RESERVOIR CHARACTERISTICS...							
Surface Area	km2	9.1	9.1	9.1	9.1	9.1	
Mean Depth	m	8.46	8.46	8.46	8.46	8.46	
Non-Algal Turbidity	1/m	0.08	0.08	0.08	0.08	0.08	
Mean Depth of Mixed Layer	m	5	5	5	5	5	
Mean Depth of Hypolimnion	m						
Observed Phosphorus	ppb		36.6	21.7	25.1	51.8	
Observed Chl-a	ppb			6	7.7	9.5	
Observed Secchi	meters		2.99	3.59	3.8	3.3	
MODEL PARAMETERS...							
BATHTUB Total P Model Number	(1-8)	1	1	1	1	1	
BATHTUB Total P Model Name		AVAIL P	AVAIL P	AVAIL P	AVAIL P	AVAIL P	(output)
BATHTUB Chl-a Model Number	(2,4,5)	4	4	4	4	4	
BATHTUB Chl-a Model Name		P-LIN	P-LIN	P-LIN	P-LIN	P-LIN	(output)
Beta = 1/S vs. C Slope	m2/mg	0.025	0.025	0.025	0.025	0.025	
P Decay Calibration		1.95	1.95	1.95	1.95	1.95	
Chlorophyll-a Calibration		0.97	0.97	0.97	0.97	0.97	
Chla Temporal Coef. of Var.		0.57	0.57	0.57	0.57	0.57	
Chla Nuisance Criterion	ppb	20	20	20	20	20	

Notes:

Drainage Area is exclusive of reservoir surface area.

Refer to BATHTUB documentation for definition of phosphorus and chlorophyll-a model numbers
Additional P Model 8 = Model 1 with availability factors set to 1.0 for total P and 0.0 for ortho P
(use if ortho phosphorus loading data are not available).

Calibration factors for phosphorus decay and chlorophyll-a are analogous to those used in BATHTUB.

Variables used in calculating algal nuisance frequencies (Walker, 1984):
Chla Temporal Coef. of Var. = within-year standard deviation of $\log_e$(chl-a)
Chla Nuisance Criterion = instantaneous chlorophyll-a associated with nuisance conditions ("bloom")

TABLE 2 - CNET.WK1 OUTPUT SECTION

CNET.WK1 VERSION 1.0		LOCH RAVEN RESERVOIR - APRIL-SEPTEMBER				
VARIABLE	UNITS	1983	1984	1985	1986	1987
WATER BALANCE...						
Precipitation Flow	hm3/yr	0.00	0.00	0.00	0.00	0.00
NonPoint Flow	hm3/yr	359.24	440.95	195.04	226.64	239.75
Point Flow	hm3/yr	0.00	0.00	0.00	0.00	0.00
Total Inflow	hm3/yr	359.24	440.95	195.04	226.64	239.75
Evaporation	hm3/yr	0.00	0.00	0.00	0.00	0.00
Outflow	hm3/yr	359.24	440.95	195.04	226.64	239.75
AVAILABLE P BALANCE...						
Precipitation Load	kg/yr	354	354	354	354	354
NonPoint Load	kg/yr	57445	65375	16215	14261	28425
Point Load	kg/yr	0	0	0	0	0
Total Load	kg/yr	57798	65728	16569	14615	28778
Sedimentation	kg/yr	41124	44858	11336	9266	20452
Outflow	kg/yr	16674	20870	5233	5349	8326
PREDICTION SUMMARY...						
P Retention Coefficient	-	0.712	0.682	0.684	0.634	0.711
Mean Phosphorus	ppb	46.4	47.3	26.8	23.6	34.7
Mean Chlorophyll-a	ppb	12.6	12.9	7.3	6.4	9.4
Algal Nuisance Frequency	%	13.7	14.4	2.0	1.1	5.4
Mean Secchi Depth	meters	2.53	2.49	3.81	4.16	3.17
Hypol. Oxygen Depletion A	mg/m2-d	852.1	860.5	647.9	607.6	737.1
Hypol. Oxygen Depletion V	mg/m3-d	ERR	ERR	ERR	ERR	ERR
Organic Nitrogen	ppb	450.4	456.1	329.2	309.2	378.1
Particulate Phosphorus	ppb	20.2	20.7	10.8	9.2	14.6
Chl-a x Secchi	mg/m2	31.9	32.0	27.8	26.7	29.9
Carlson TSI P		59.5	59.8	51.6	49.8	55.4
Carlson TSI Chl-a		55.5	55.7	50.1	48.8	52.6
Carlson TSI Secchi		46.6	46.8	40.7	39.4	43.4
OBSERVED / PREDICTED RATIOS...						
Phosphorus		0.00	0.77	0.81	1.06	1.49
Chlorophyll-a		0.00	0.00	0.82	1.20	1.01
Secchi		0.00	1.20	0.94	0.91	1.04
OBSERVED / PREDICTED T-STATISTICS...						
Phosphorus		ERR	-0.95	-0.78	0.23	1.47
Chlorophyll-a		ERR	ERR	-0.56	0.52	0.02
Secchi		ERR	0.65	-0.22	-0.32	0.15

Notes:

OBSERVED / PREDICTED T-STATISTIC = [log10(Observed Value) - log10(Predicted Value)] / SE

SE = residual standard error derived from model development data set.

A |T| value greater than 2.0 suggests that the deviation between observed and predicted value is unusually large.

Algal Nuisance Frequency = % of time chlorophyll-a exceeds nuisance criterion specified in input section.

TABLE 3 - CNET.WK1 CALCULATION SECTION

CNET.WK1 VERSION 1.0		LOCH RAVEN RESERVOIR - APRIL-SEPTEMBER				
VARIABLE	UNITS	1983	1984	1985	1986	1987
RESPONSE CALCULATIONS...						
Reservoir Volume	hm3	76.986	76.986	76.986	76.986	76.986
Residence Time	yrs	0.2143	0.1746	0.3947	0.3397	0.3211
Overflow Rate	m/yr	39.5	48.5	21.4	24.9	26.3
Total P Availability Factor		0.33	0.33	0.33	0.33	0.33
Ortho P Availability Factor		1.93	1.93	1.93	1.93	1.93
Inflow Ortho P/Total P		0.193	0.192	0.285	0.252	0.221
Inflow P Conc	ppb	160.9	149.1	85.0	64.5	120.0
P Reaction Rate - Mods 1 & 8		8.5	6.8	6.9	4.7	8.5
P Reaction Rate - Model 2		14.6	11.6	7.9	6.2	12.7
P Reaction Rate - Model 3		6.7	5.1	6.5	4.3	7.5
1-Rp Model 1 - Avail P		0.288	0.318	0.316	0.366	0.289
1-Rp Model 2 - Decay Rate		0.230	0.253	0.297	0.329	0.244
1-Rp Model 3 - 2nd Order Fixed		0.318	0.356	0.322	0.381	0.304
1-Rp Model 4 - Canfield & Bachman		0.304	0.332	0.332	0.383	0.306
1-Rp Model 5 - Vollenweider 1976		0.526	0.551	0.449	0.468	0.475
1-Rp Model 6 - First Order Decay		0.705	0.746	0.565	0.602	0.615
1-Rp Model 7 - First Order Setting		0.953	0.961	0.917	0.927	0.931
1-Rp Model 8 - 2nd Order Tp Only		0.288	0.318	0.316	0.366	0.289
1-Rp - Used		0.288	0.318	0.316	0.366	0.289
Reservoir P Conc	ppb	46.4	47.3	26.8	23.6	34.7
Gp		1.048	1.070	1.003	1.012	1.015
Bp	ppb	39.3	40.4	18.6	15.6	26.4
Chla vs. P, Turb, Flushing	2	17.3	17.3	11.4	10.0	14.2
Chla vs. P Linear	4	12.6	12.9	7.3	6.4	9.4
Chla vs. P 1.46	5	21.3	21.9	9.6	7.9	14.0
Chla Used	ppb	12.6	12.9	7.3	6.4	9.4
ml - Nuisance Freq Calc.		2.4	2.4	1.8	1.7	2.1
z		1.095	1.060	2.056	2.281	1.604
v		0.219	0.227	0.048	0.030	0.110
w		0.733	0.739	0.594	0.569	0.652
x		0.137	0.144	0.020	0.011	0.054
ORTHO P LOADS...						
Precipitation	kg/yr	137	137	137	137	137
NonPoint	kg/yr	15735	17859	5227	4374	8271
Point	kg/yr	0	0	0	0	0
Total	kg/yr	15871	17995	5364	4511	8408
TOTAL P LOADS...						
Precipitation	kg/yr	273	273	273	273	273
NonPoint	kg/yr	82050	93659	18568	17633	37761
Point	kg/yr	0	0	0	0	0
Total	kg/yr	82323	93932	18841	17906	38034

Note:

Above portion of worksheet contains intermediate calculations.