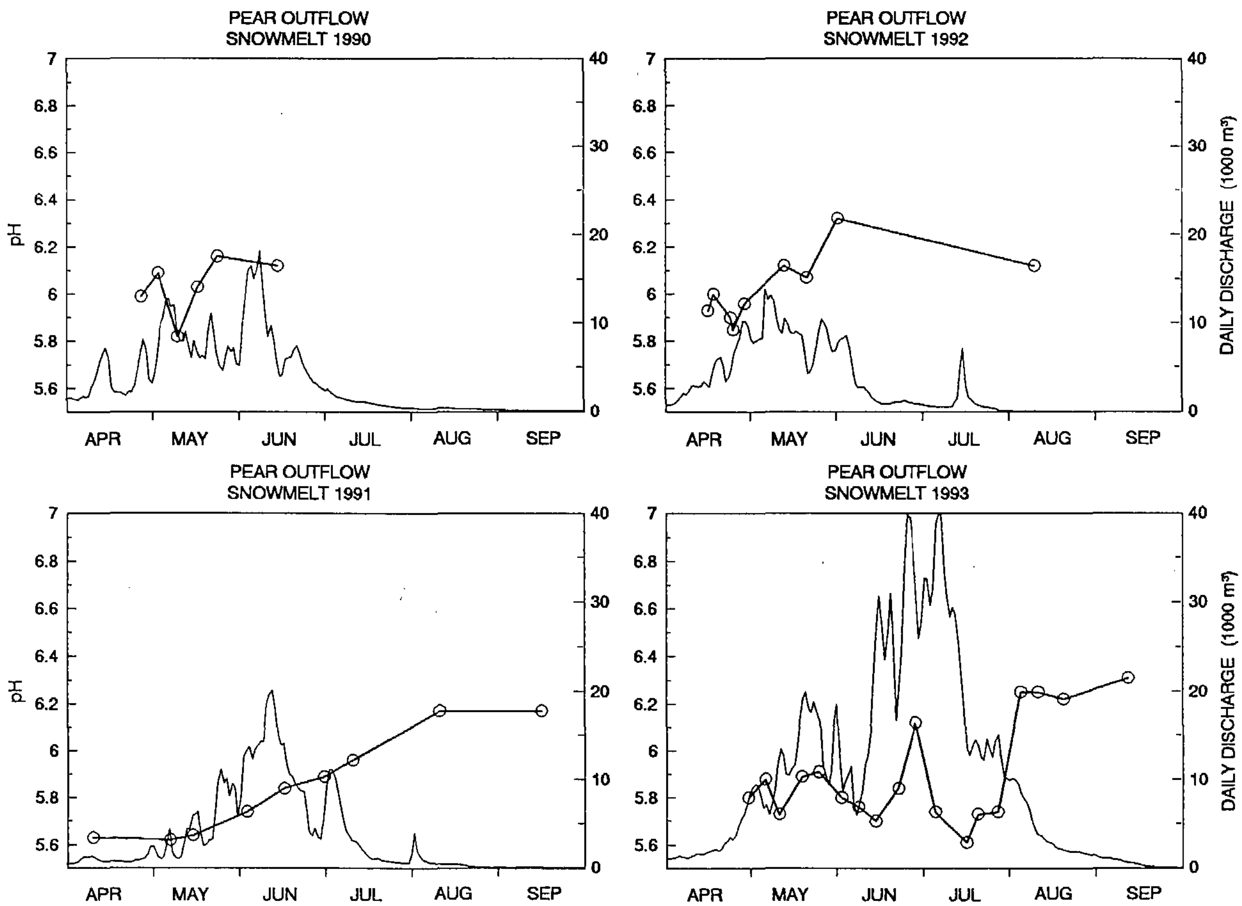

PEAR OUTFLOW
SNOWMELT 1990
PEAR OUTFLOW
SNOWMELT 1992
PEAR OUTFLOW
SNOWMELT 1991
PEAR OUTFLOW
SNOWMELT 1993
pH
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-41

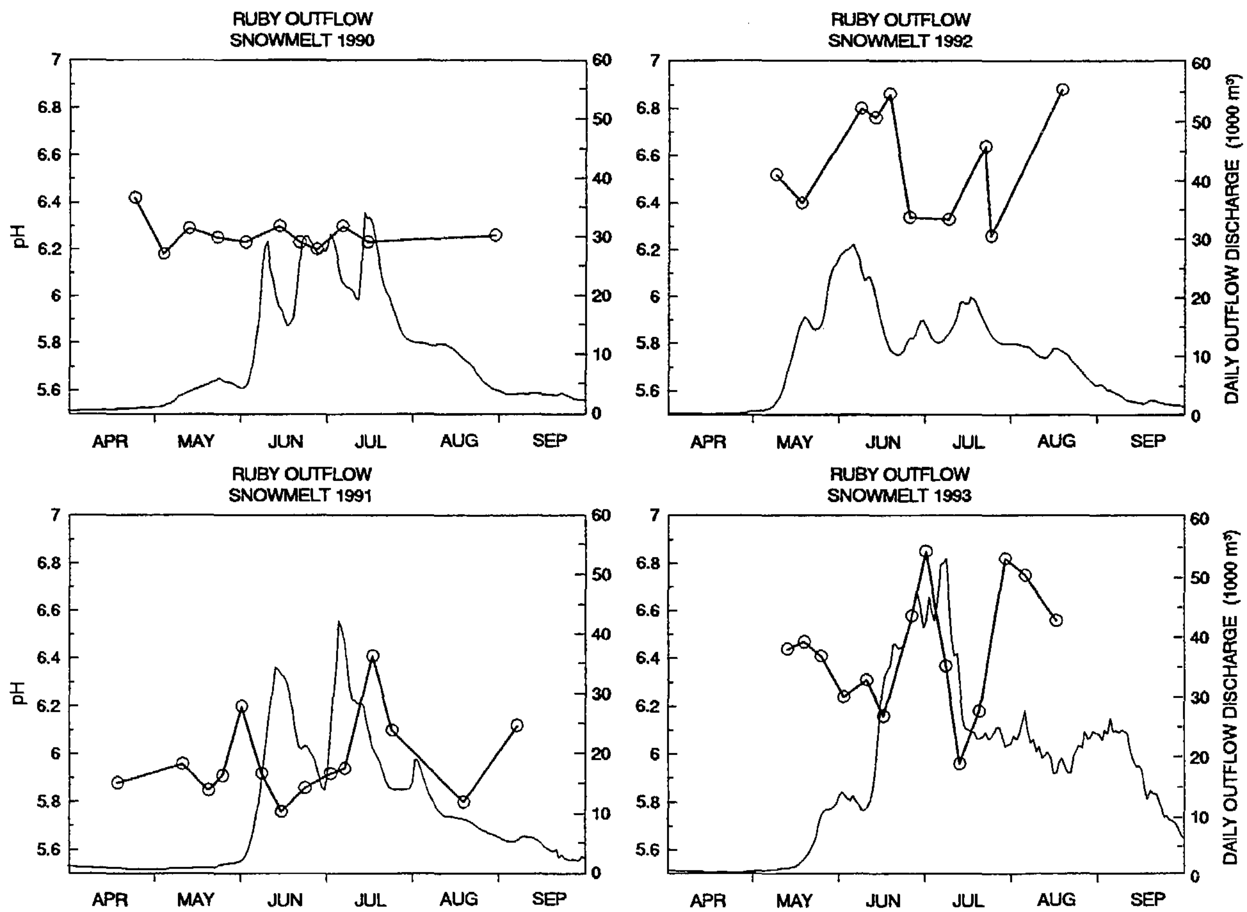

RUBY OUTFLOW
SNOWMELT 1990
RUBY OUTFLOW
SNOWMELT 1992
RUBY OUTFLOW
SNOWMELT 1991
RUBY OUTFLOW
SNOWMELT 1993
pH
DAILY OUTFLOW DISCHARGE (1000 m³)
7
6.8
6.6
6.4
6.2
6
5.8
5.6
60
50
40
30
20
10
0
APR
MAY
JUN
JUL
AUG
SEP

Figure I-42

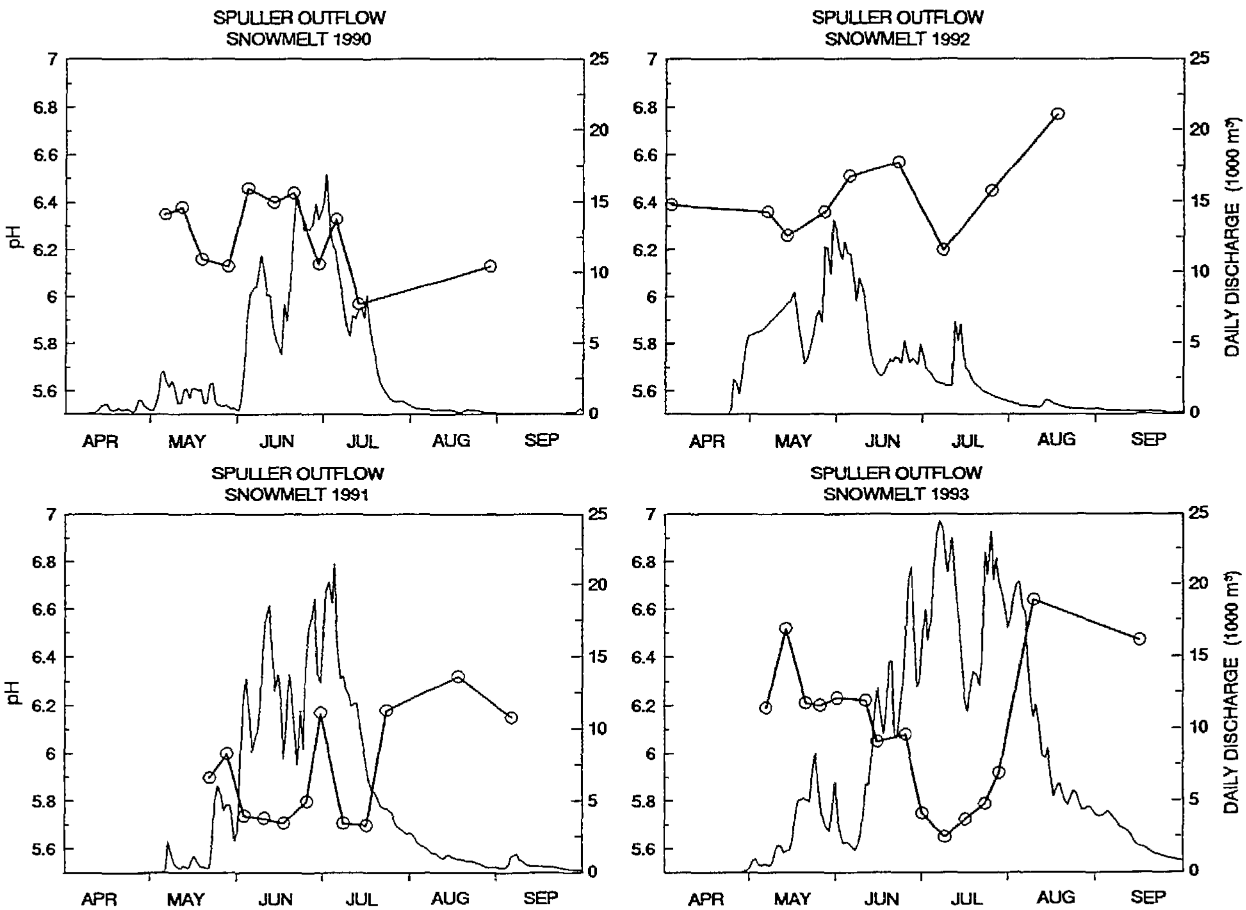

SPULLER OUTFLOW
SNOWMELT 1990
SPULLER OUTFLOW
SNOWMELT 1992
SPULLER OUTFLOW
SNOWMELT 1991
SPULLER OUTFLOW
SNOWMELT 1993
pH
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-43

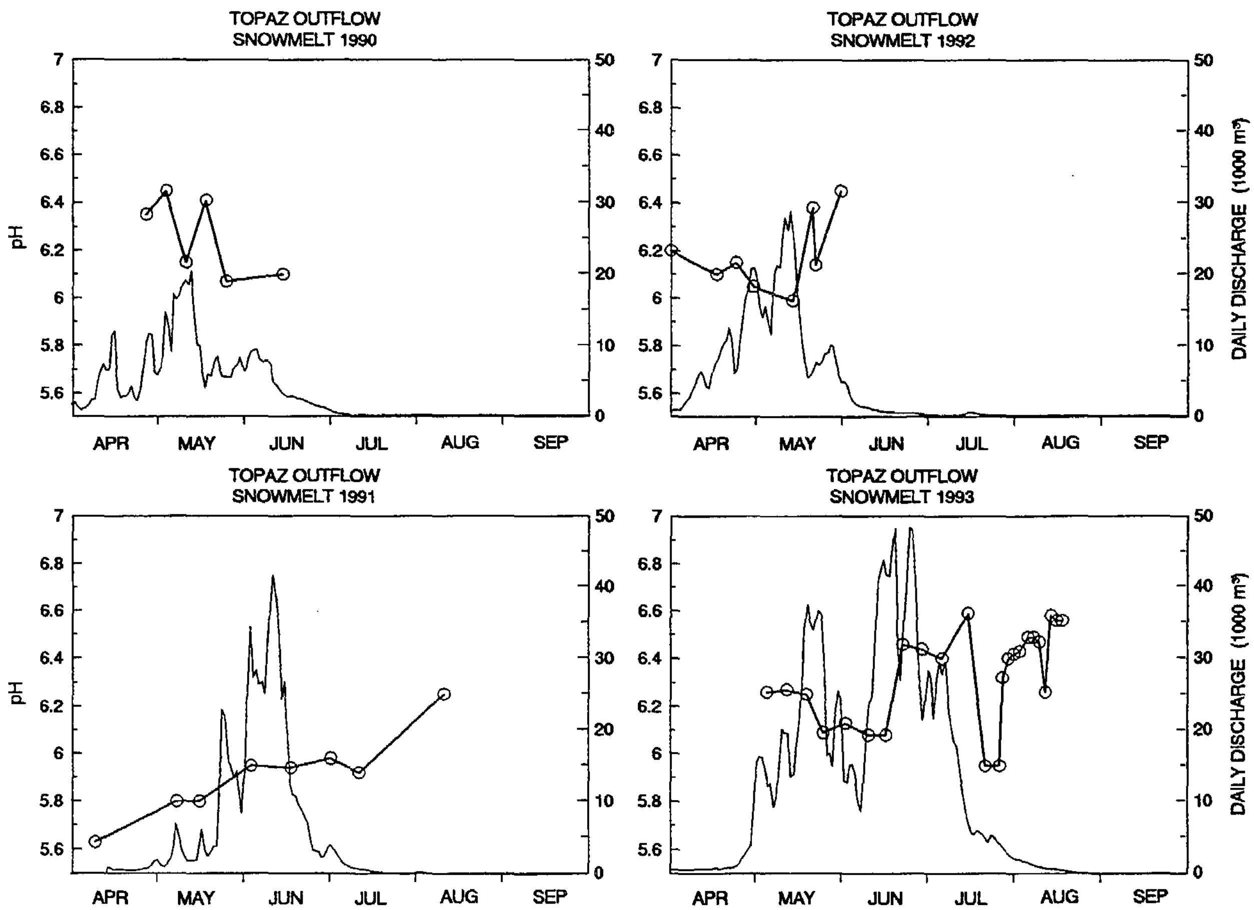
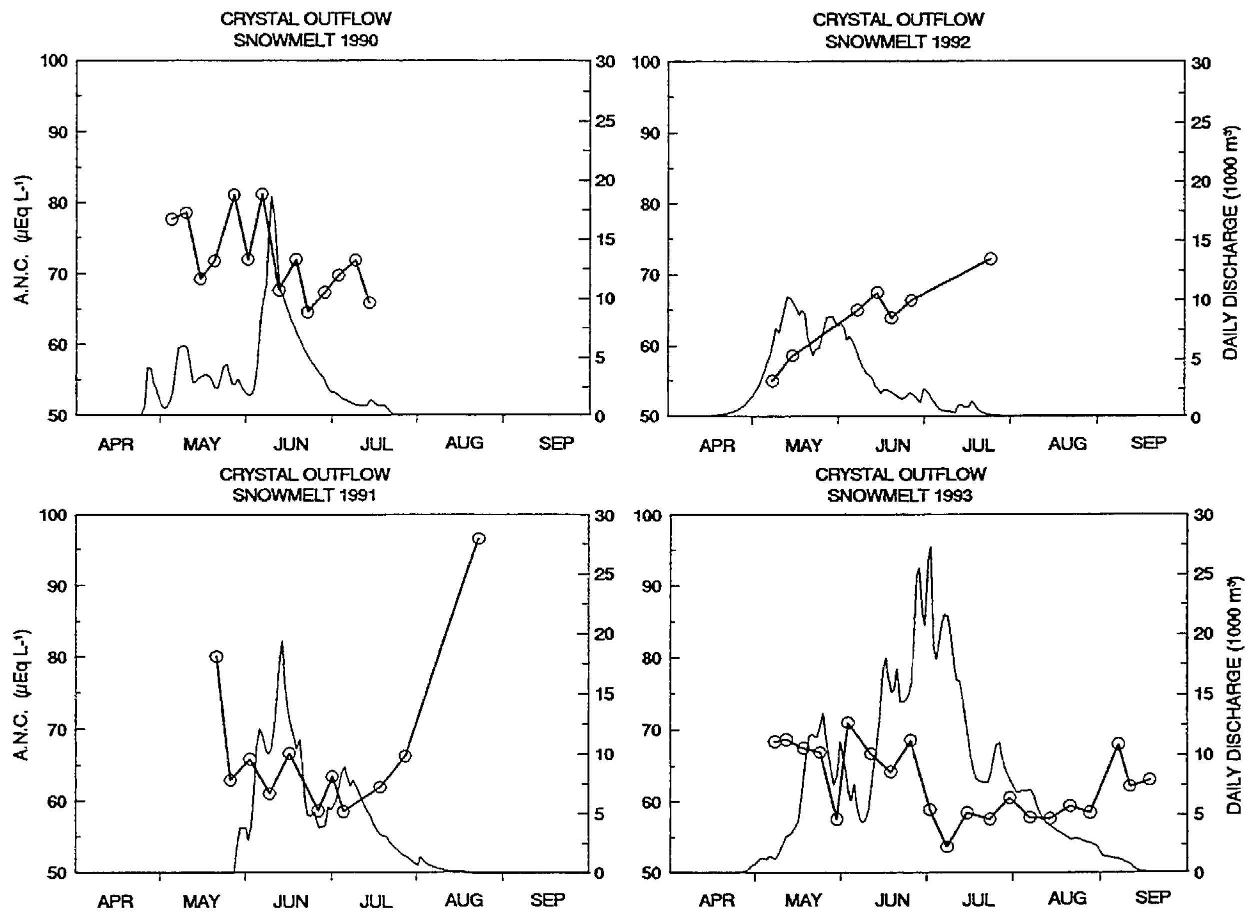

TOPAZ OUTFLOW
SNOWMELT 1990
TOPAZ OUTFLOW
SNOWMELT 1992
TOPAZ OUTFLOW
SNOWMELT 1991
TOPAZ OUTFLOW
SNOWMELT 1993
pH
DAILY DISCHARGE (1000 m³)
7
6.8
6.6
6.4
6.2
6
5.8
5.6
50
40
30
20
10
0
APR
MAY
JUN
JUL
AUG
SEP

Figure I-44



CRYSTAL OUTFLOW
SNOWMELT 1990
CRYSTAL OUTFLOW
SNOWMELT 1992
CRYSTAL OUTFLOW
SNOWMELT 1991
CRYSTAL OUTFLOW
SNOWMELT 1993
A.N.C. (μEq L⁻¹)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-45

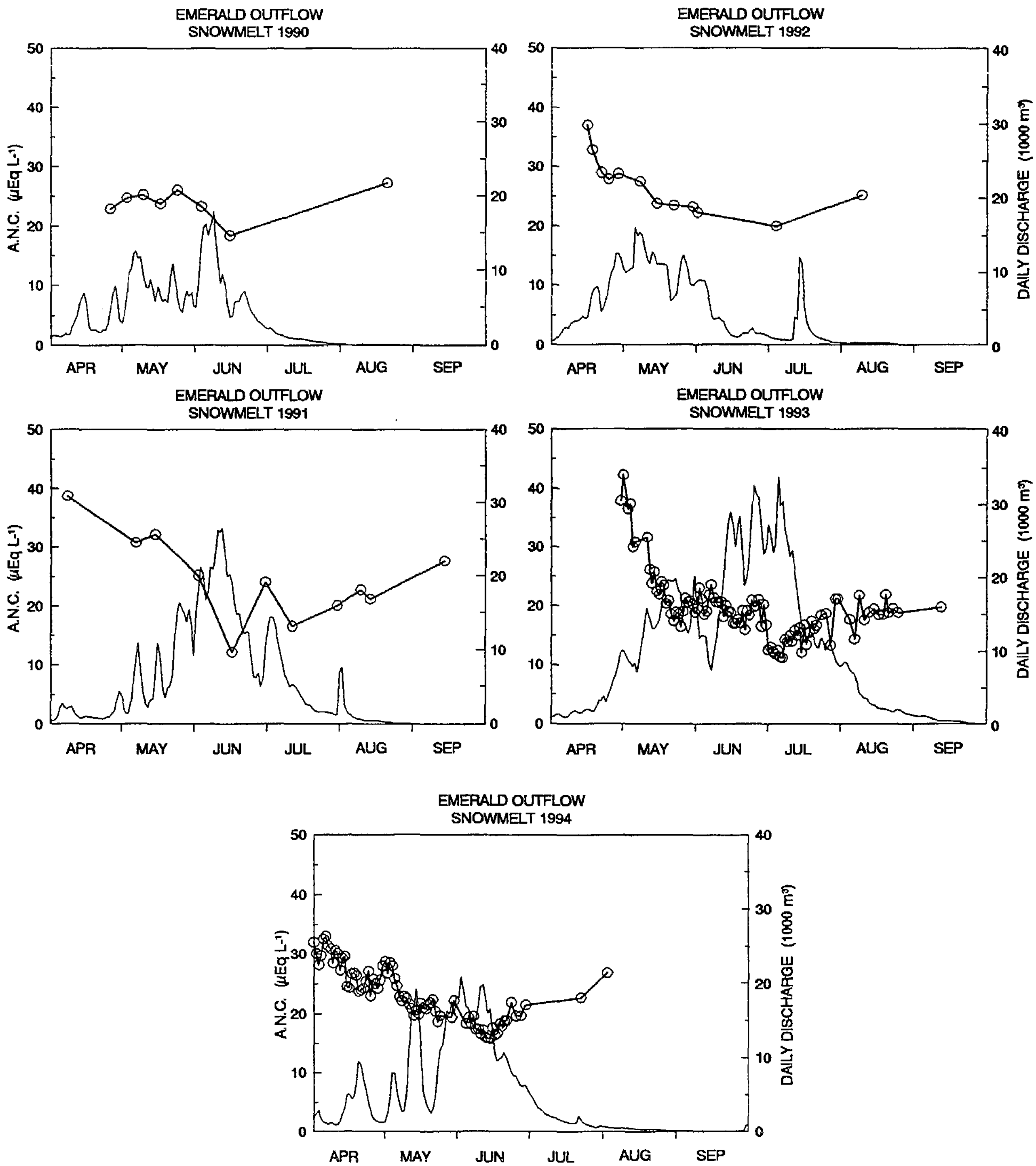

EMERALD OUTFLOW
SNOWMELT 1990
EMERALD OUTFLOW
SNOWMELT 1992
EMERALD OUTFLOW
SNOWMELT 1991
EMERALD OUTFLOW
SNOWMELT 1993
EMERALD OUTFLOW
SNOWMELT 1994
A.N.C. (μEq L-1)
DAILY DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-46

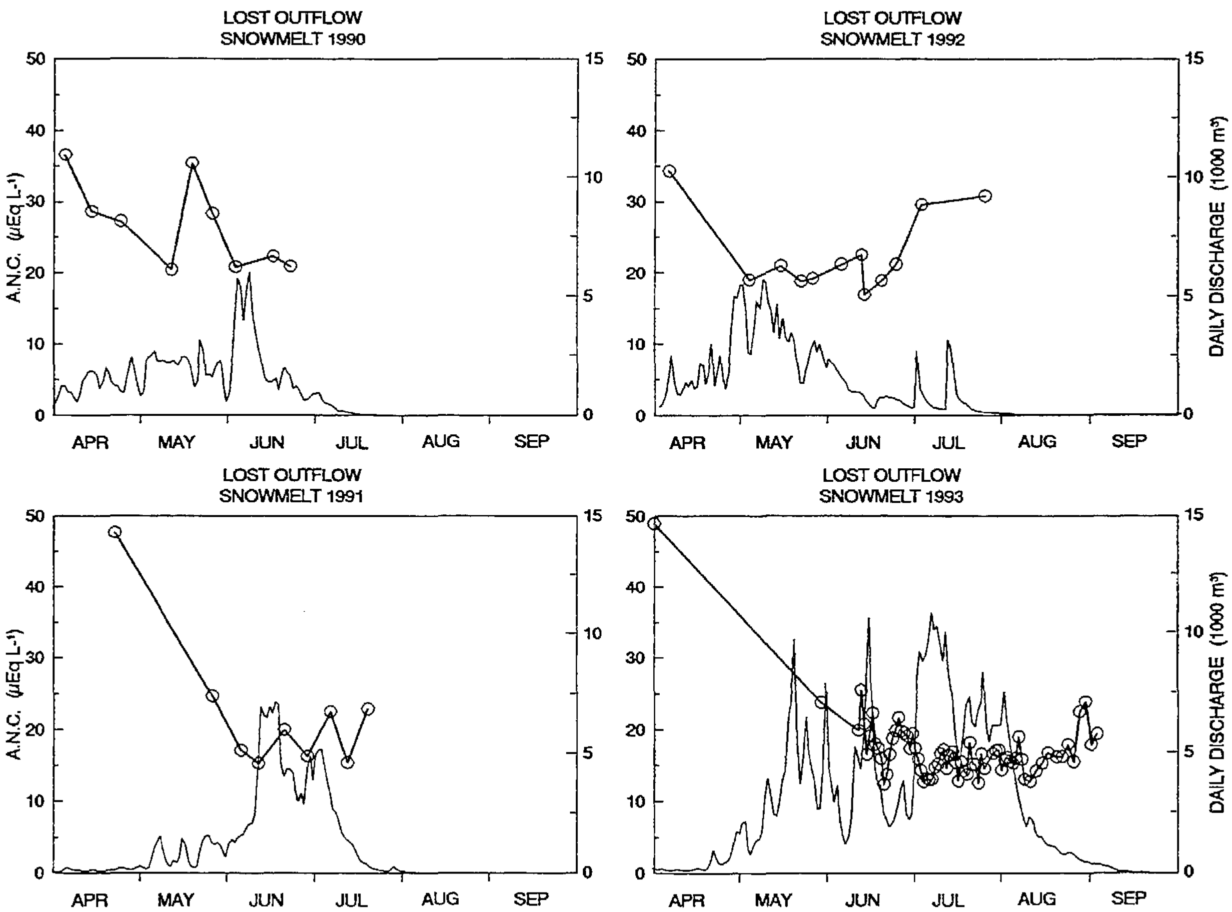
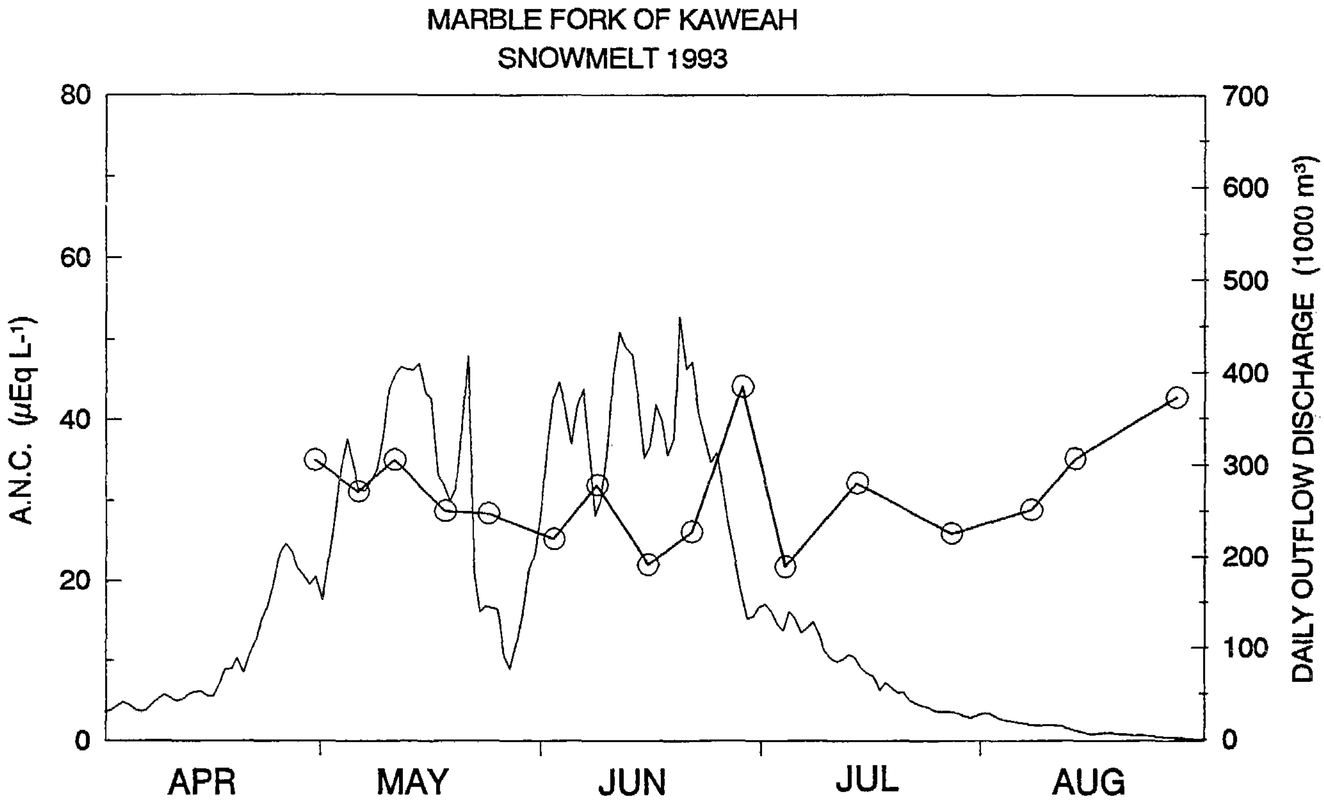

LOST OUTFLOW
SNOWMELT 1990
LOST OUTFLOW
SNOWMELT 1992
LOST OUTFLOW
SNOWMELT 1991
LOST OUTFLOW
SNOWMELT 1993
A.N.C. (μEq L⁻¹)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-47


MARBLE FORK OF KAWEAH
SNOWMELT 1993
A.N.C. (μEq L-1)
DAILY OUTFLOW DISCHARGE (1000 m3)
0
20
40
60
80
0
100
200
300
400
500
600
700
APR
MAY
JUN
JUL
AUG

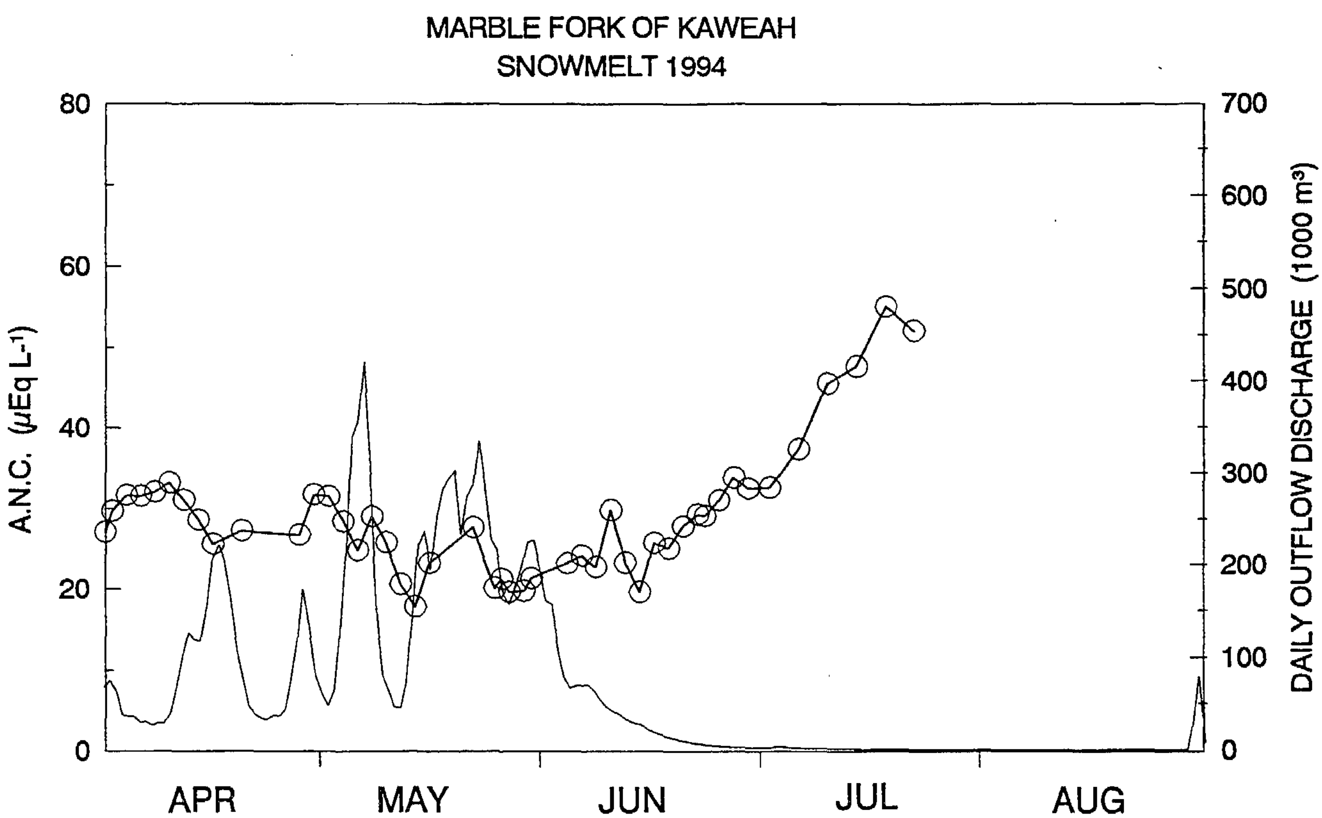

MARBLE FORK OF KAWEAH
SNOWMELT 1994
A.N.C. (μEq L-1)
DAILY OUTFLOW DISCHARGE (1000 m3)
0
20
40
60
80
0
100
200
300
400
500
600
700
APR
MAY
JUN
JUL
AUG

Figure I-48

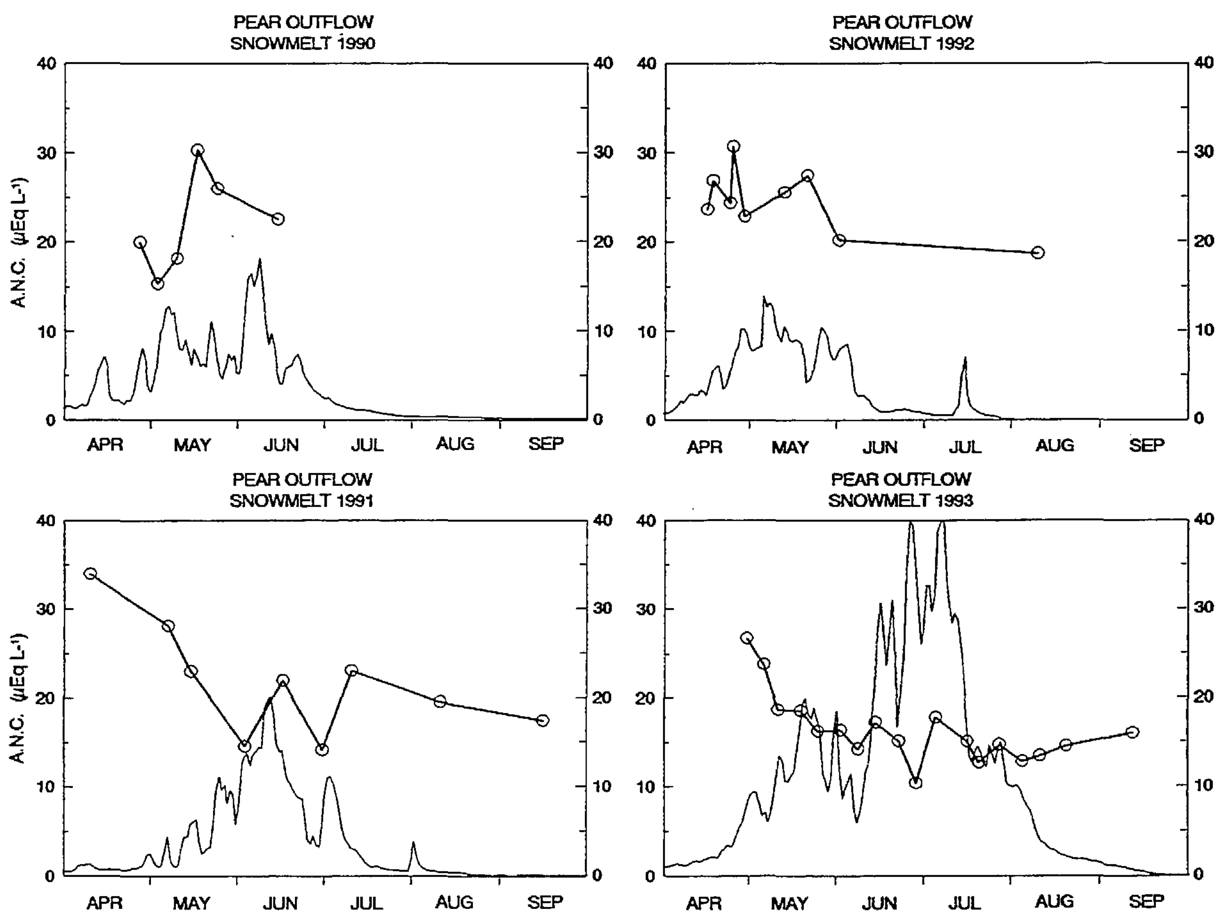

PEAR OUTFLOW
SNOWMELT 1990
PEAR OUTFLOW
SNOWMELT 1992
PEAR OUTFLOW
SNOWMELT 1991
PEAR OUTFLOW
SNOWMELT 1993
A.N.C. (μEq L⁻¹)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP
0
10
20
30
40

Figure I-49

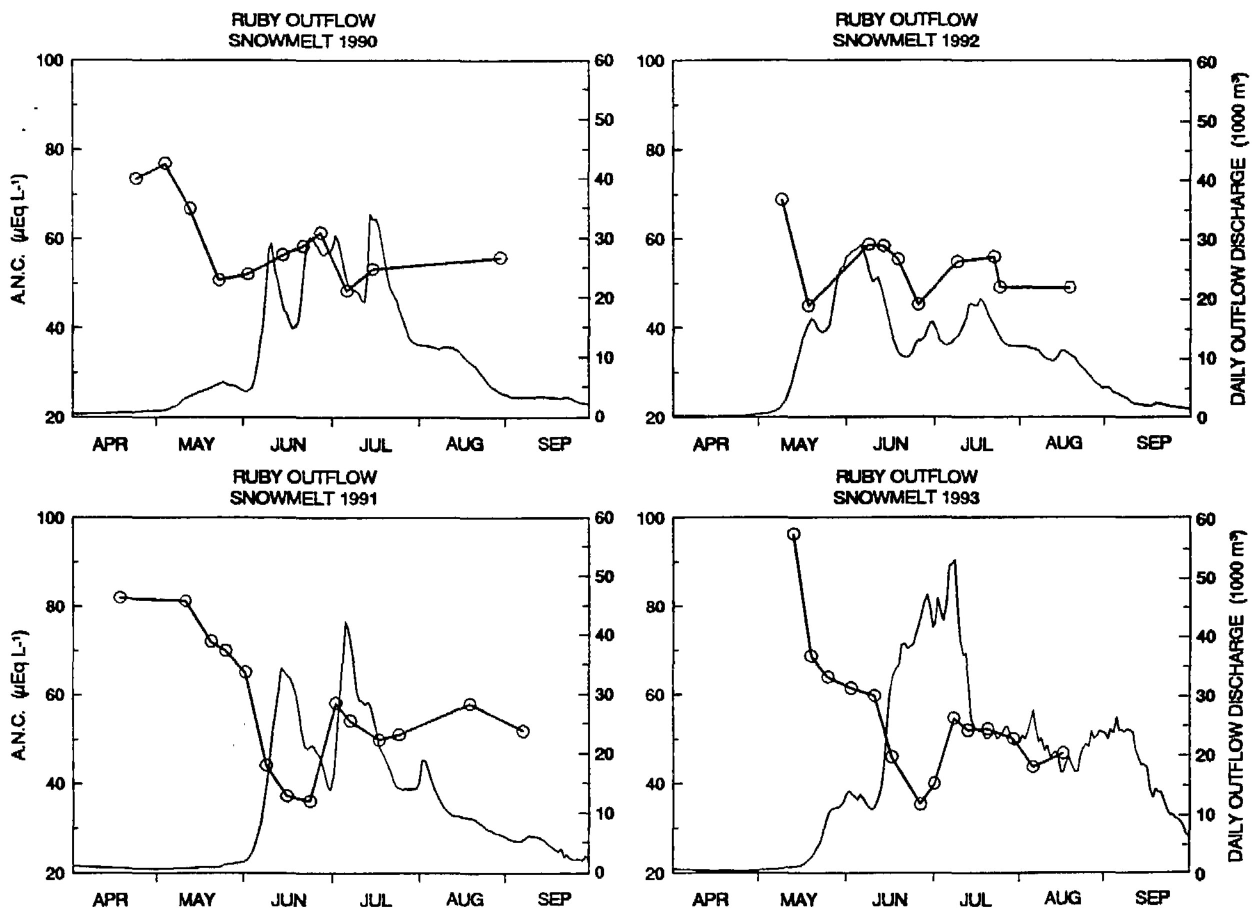

RUBY OUTFLOW
SNOWMELT 1990
RUBY OUTFLOW
SNOWMELT 1992
RUBY OUTFLOW
SNOWMELT 1991
RUBY OUTFLOW
SNOWMELT 1993
A.N.C. (μEq L⁻¹)
DAILY OUTFLOW DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP
100
80
60
40
20
60
50
40
30
20
10
0

Figure I-50

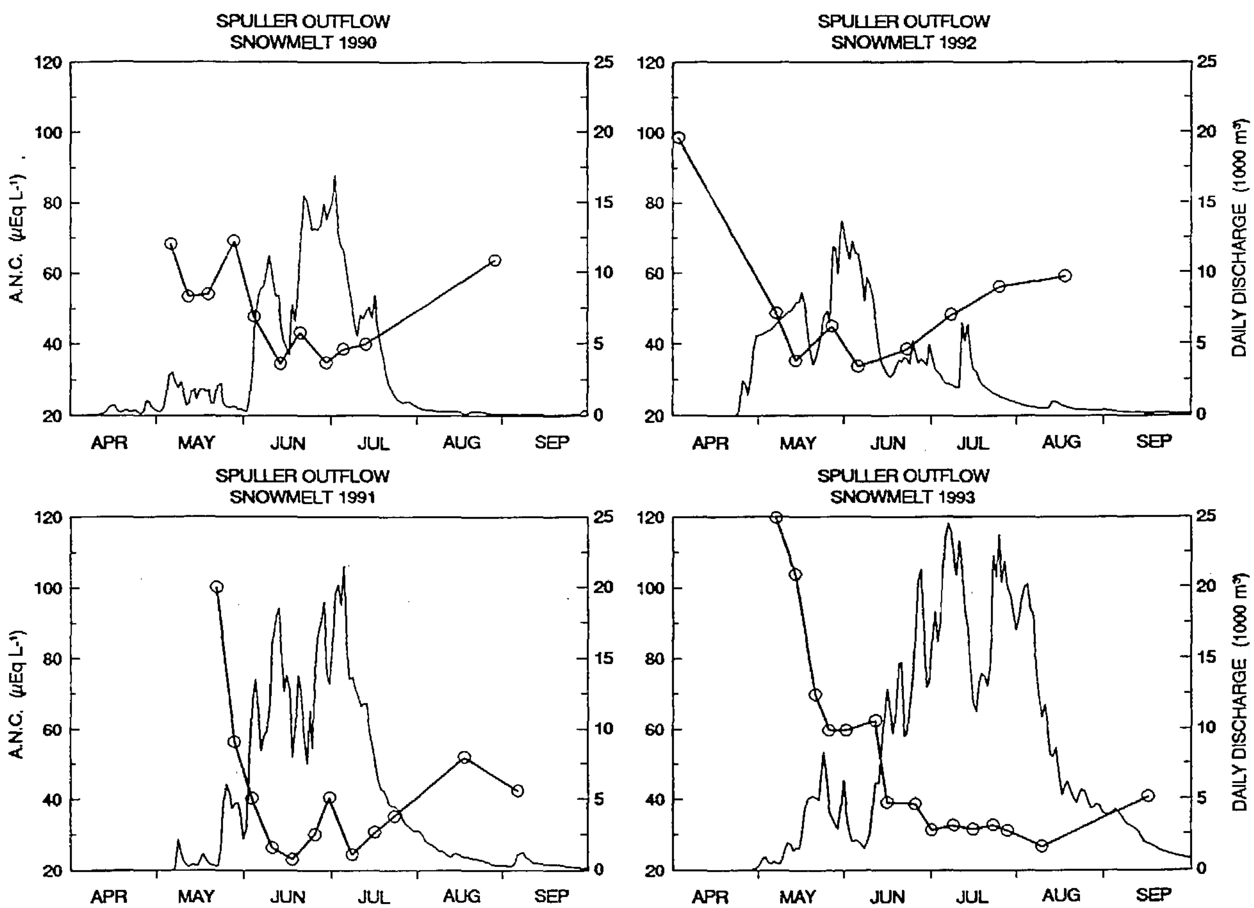
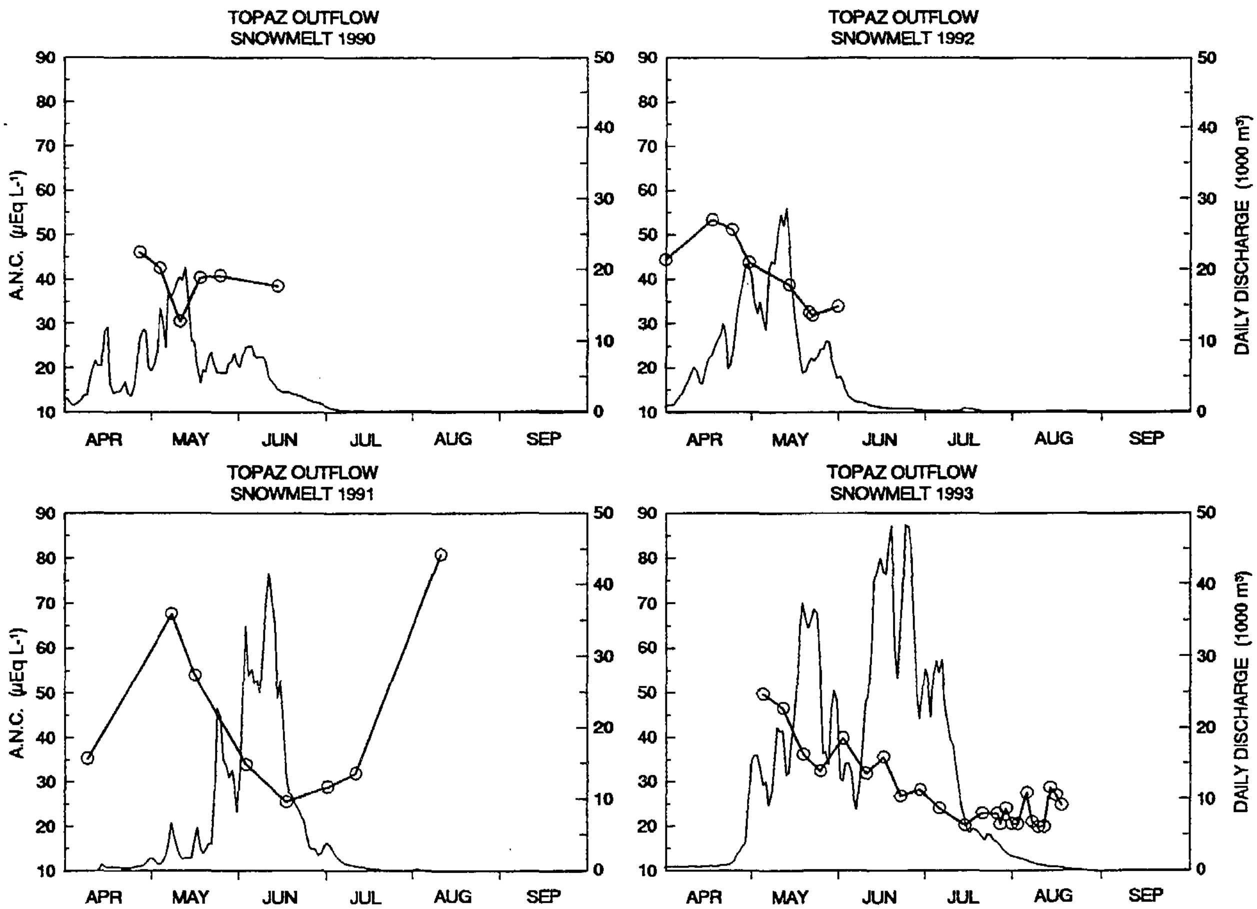

SPULLER OUTFLOW
SNOWMELT 1990
SPULLER OUTFLOW
SNOWMELT 1992
SPULLER OUTFLOW
SNOWMELT 1991
SPULLER OUTFLOW
SNOWMELT 1993
A.N.C. (μEq L⁻¹)
DAILY DISCHARGE (1000 m³)
APR MAY JUN JUL AUG SEP

Figure I-51



TOPAZ OUTFLOW
SNOWMELT 1990
TOPAZ OUTFLOW
SNOWMELT 1992
TOPAZ OUTFLOW
SNOWMELT 1991
TOPAZ OUTFLOW
SNOWMELT 1993
A.N.C. (μEq L-1)
DAILY DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-52

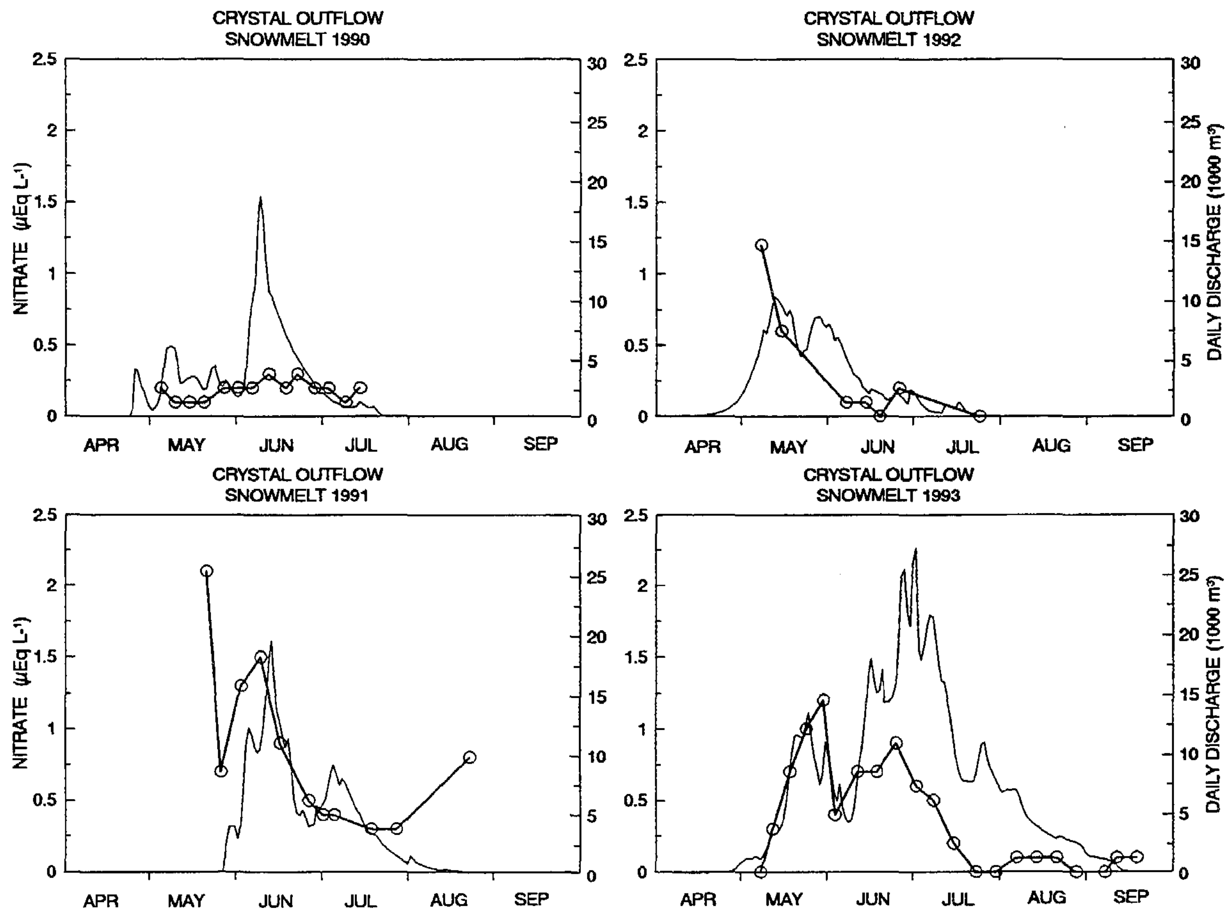

CRYSTAL OUTFLOW
SNOWMELT 1990
CRYSTAL OUTFLOW
SNOWMELT 1992
CRYSTAL OUTFLOW
SNOWMELT 1991
CRYSTAL OUTFLOW
SNOWMELT 1993
NITRATE (μEq L⁻¹)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP
0
0.5
1
1.5
2
2.5
0
5
10
15
20
25
30

Figure I-53

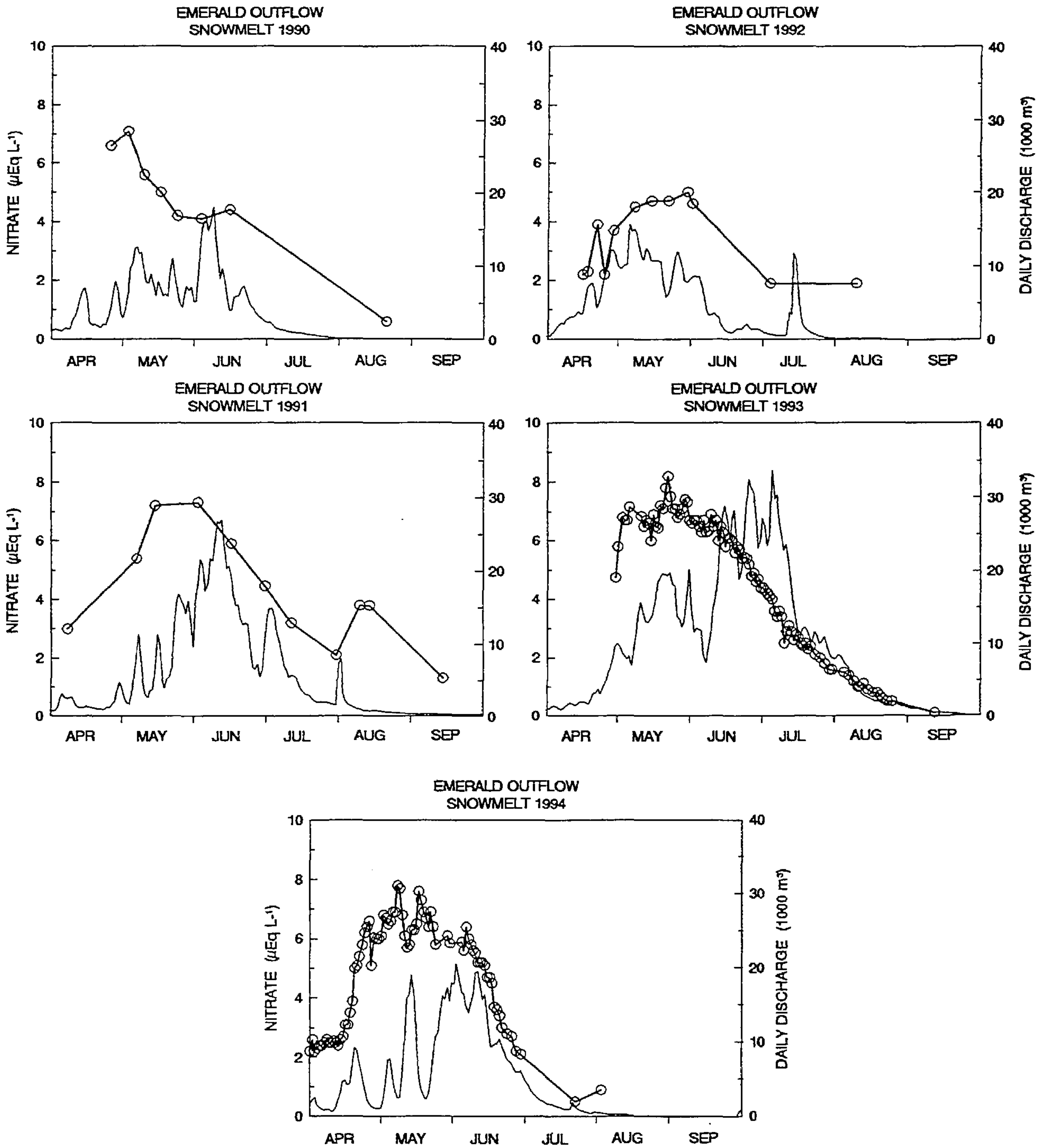

EMERALD OUTFLOW
SNOWMELT 1990
EMERALD OUTFLOW
SNOWMELT 1992
EMERALD OUTFLOW
SNOWMELT 1991
EMERALD OUTFLOW
SNOWMELT 1993
EMERALD OUTFLOW
SNOWMELT 1994
NITRATE (µEq L-1)
DAILY DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-54

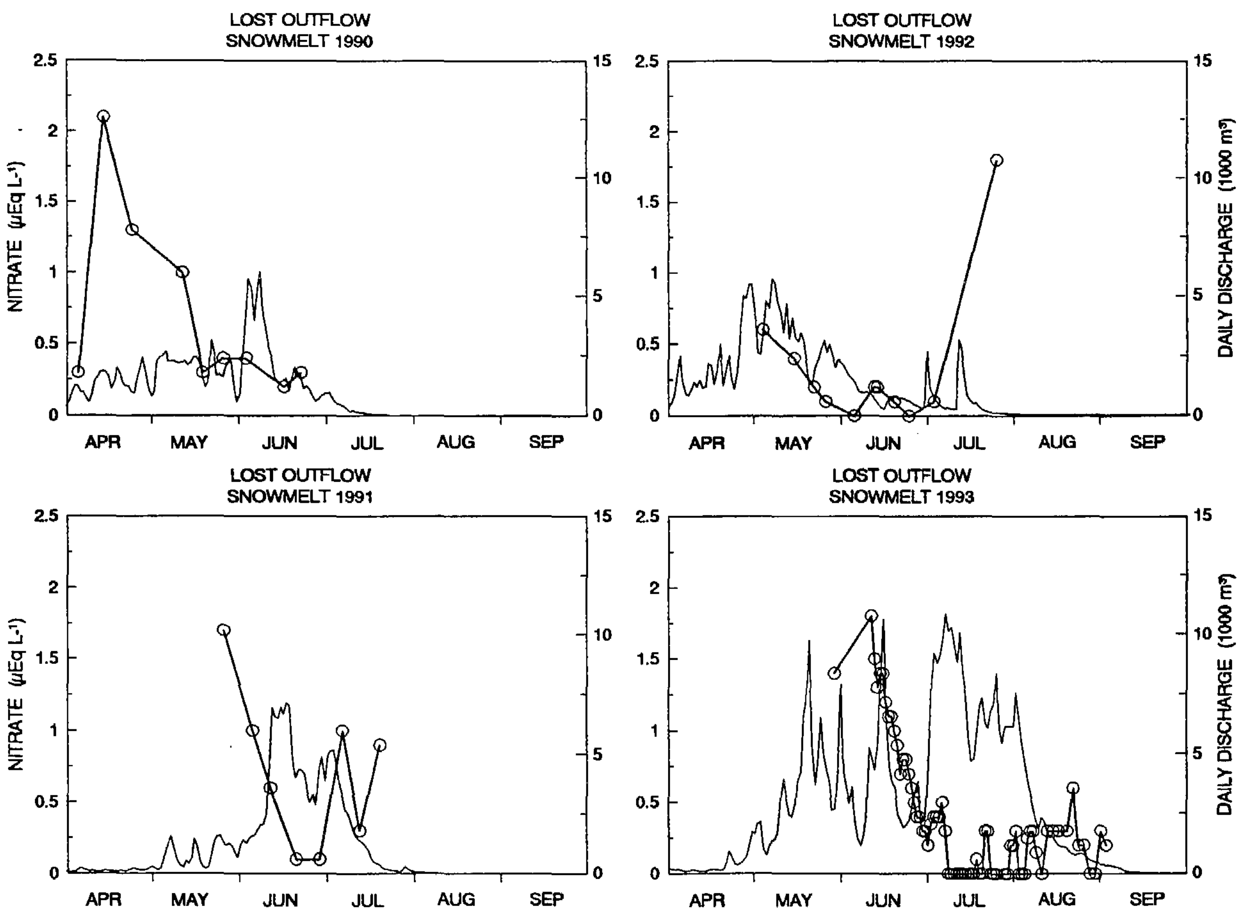

LOST OUTFLOW
SNOWMELT 1990
LOST OUTFLOW
SNOWMELT 1992
LOST OUTFLOW
SNOWMELT 1991
LOST OUTFLOW
SNOWMELT 1993
NITRATE (μEq L-1)
DAILY DISCHARGE (1000 m3)
0
0.5
1
1.5
2
2.5
0
5
10
15
APR
MAY
JUN
JUL
AUG
SEP

Figure I-55

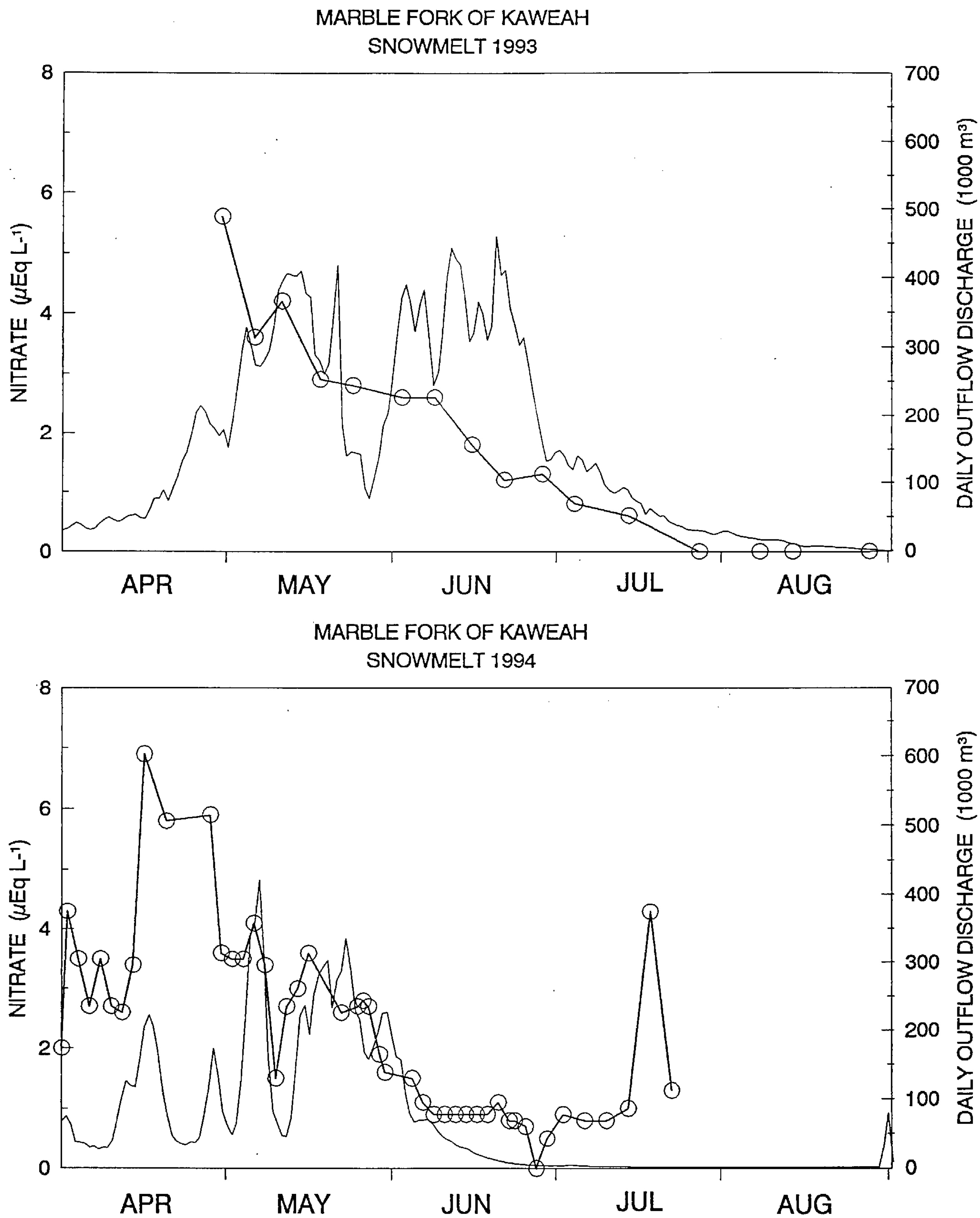

MARBLE FORK OF KAWEAH
SNOWMELT 1993
NITRATE (μEq L-1)
DAILY OUTFLOW DISCHARGE (1000 m3)
0
2
4
6
8
0
100
200
300
400
500
600
700
APR
MAY
JUN
JUL
AUG
MARBLE FORK OF KAWEAH
SNOWMELT 1994
NITRATE (μEq L-1)
DAILY OUTFLOW DISCHARGE (1000 m3)
0
2
4
6
8
0
100
200
300
400
500
600
700
APR
MAY
JUN
JUL
AUG

Figure I-56

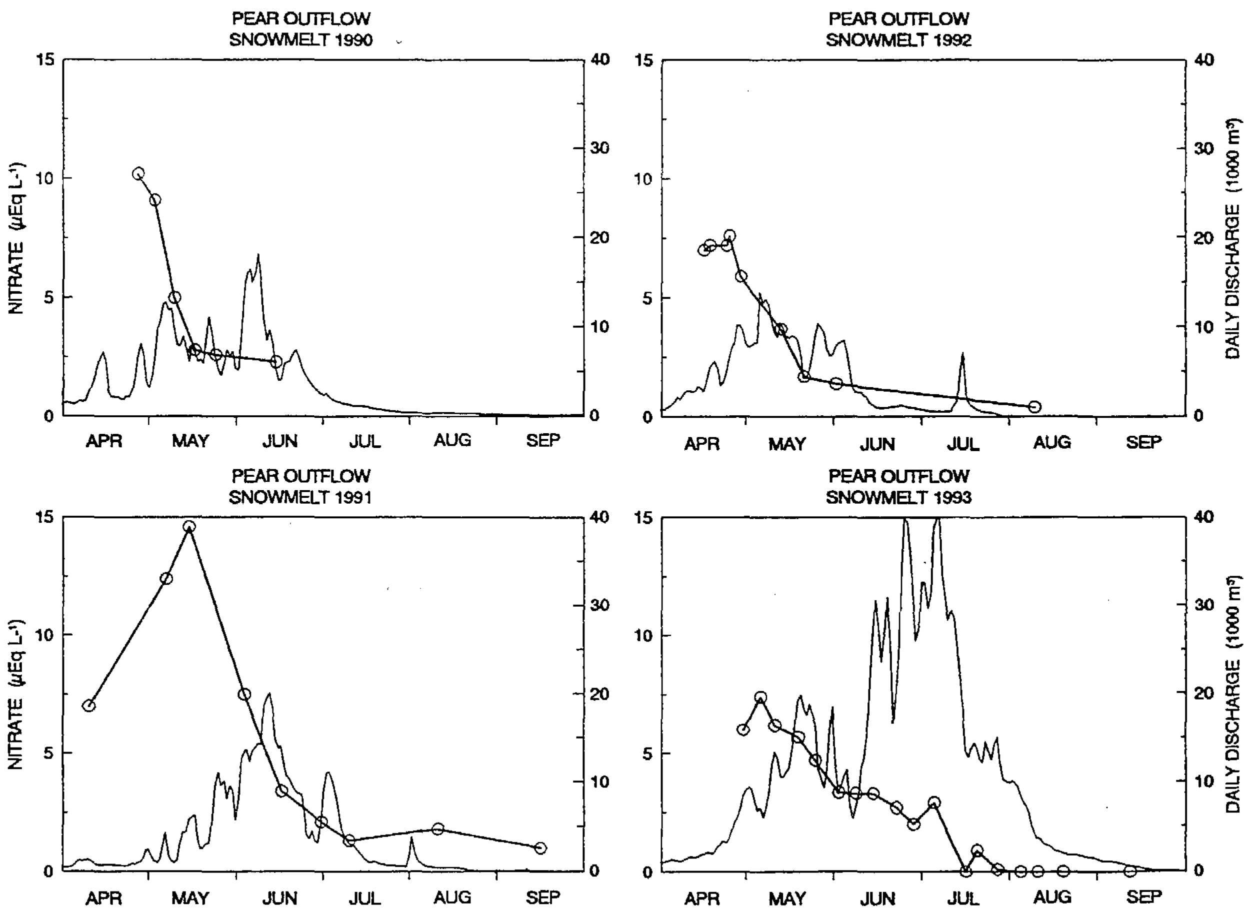

PEAR OUTFLOW
SNOWMELT 1990
PEAR OUTFLOW
SNOWMELT 1992
PEAR OUTFLOW
SNOWMELT 1991
PEAR OUTFLOW
SNOWMELT 1993
NITRATE (µEq L⁻¹)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP
0
5
10
15
20
30
40

Figure I-57

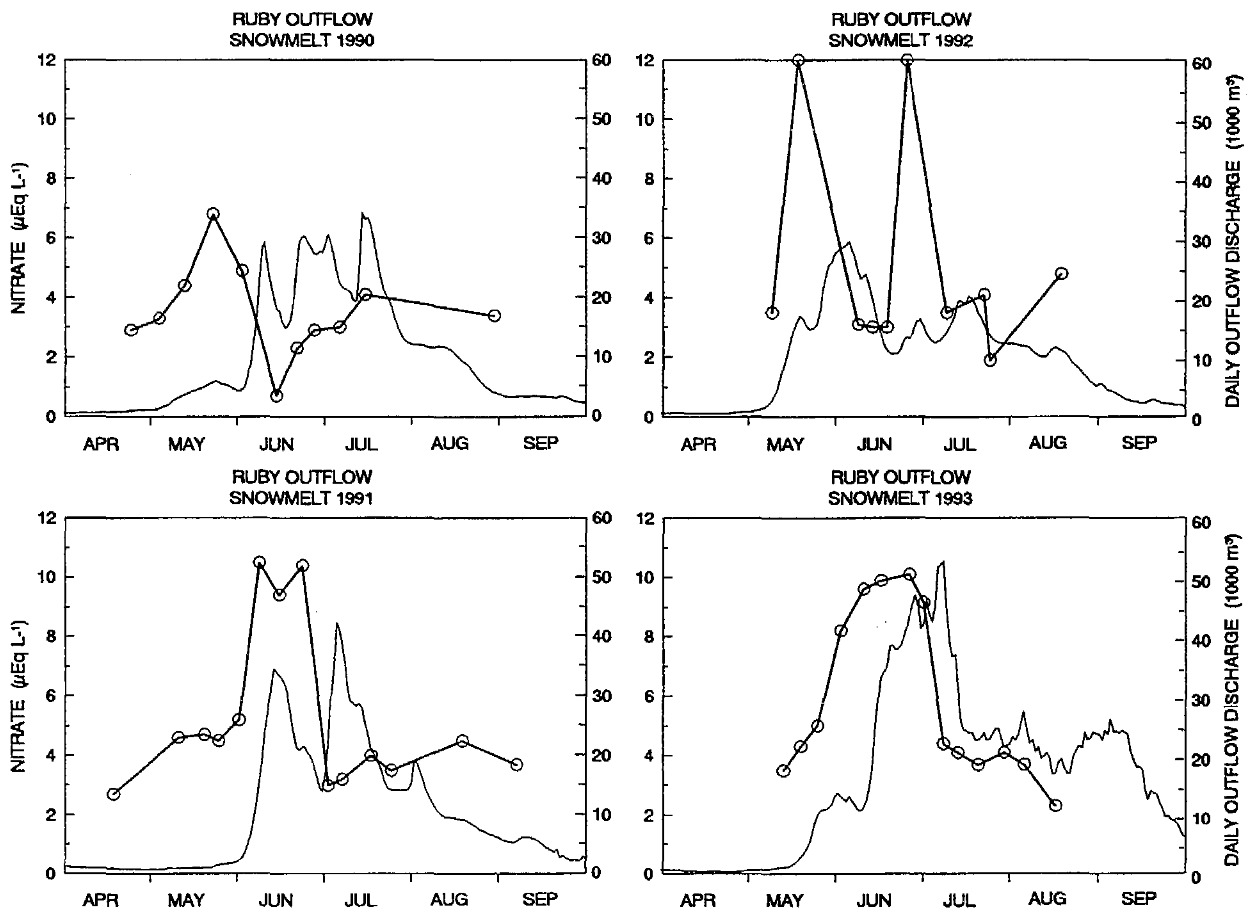

RUBY OUTFLOW
SNOWMELT 1990
RUBY OUTFLOW
SNOWMELT 1992
RUBY OUTFLOW
SNOWMELT 1991
RUBY OUTFLOW
SNOWMELT 1993
NITRATE (μEq L-1)
DAILY OUTFLOW DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-58

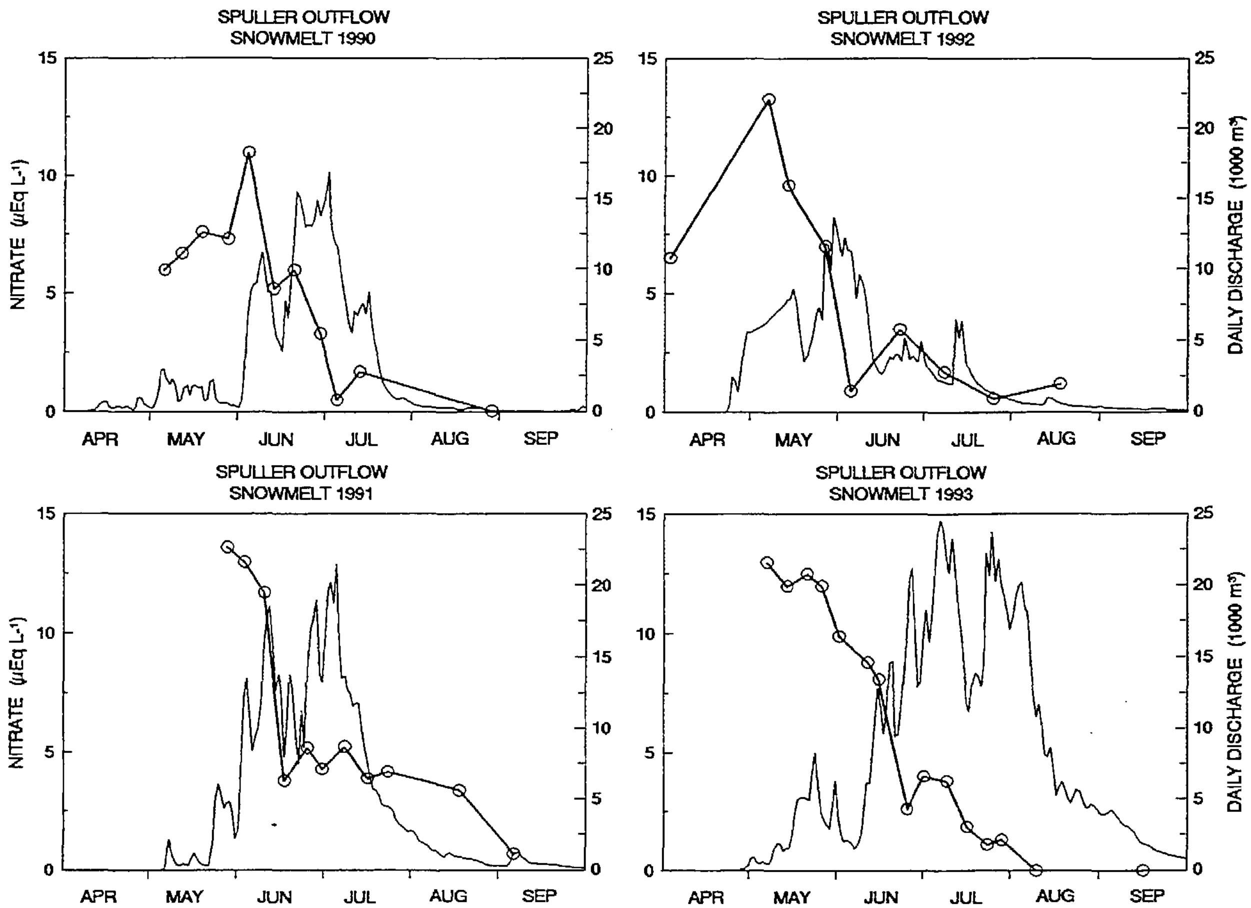
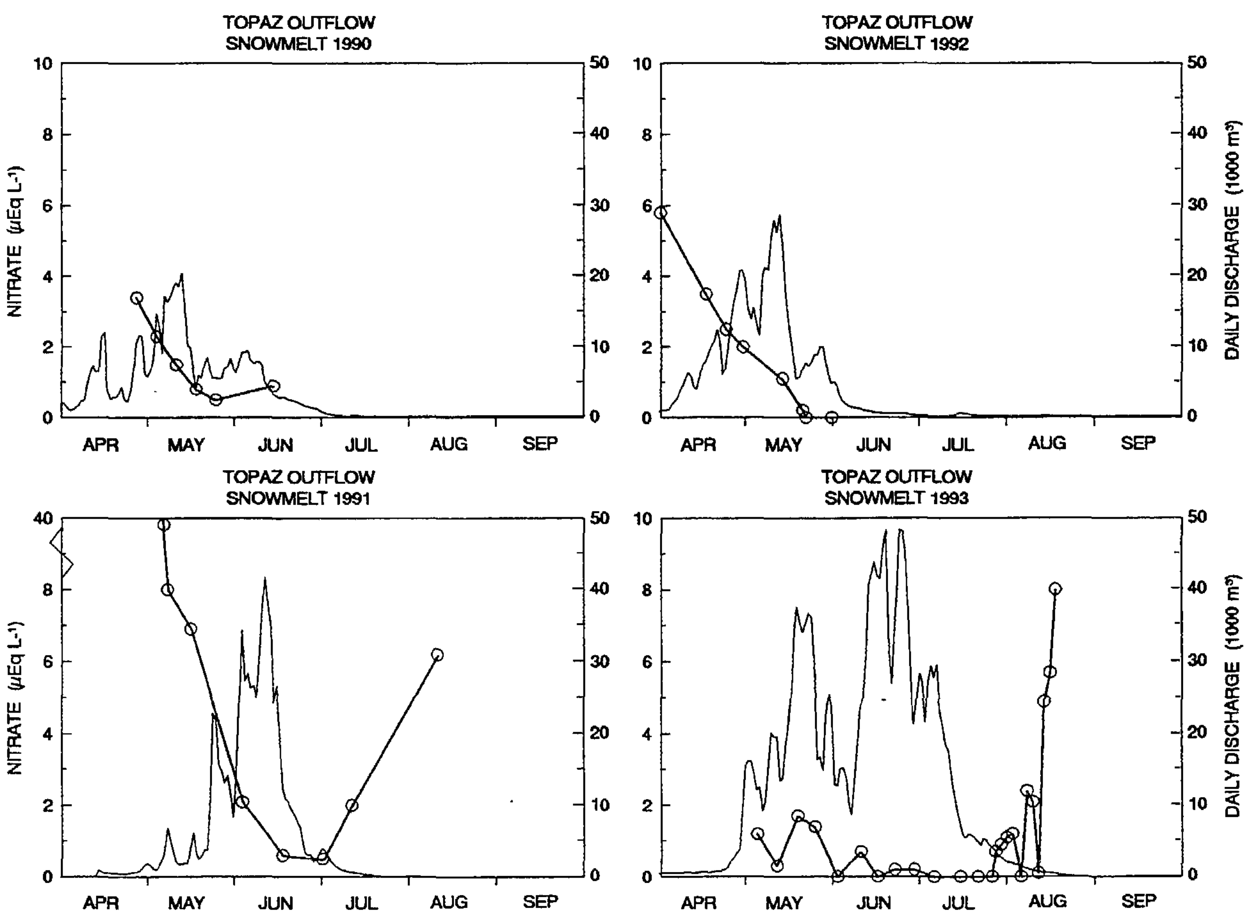

SPULLER OUTFLOW
SNOWMELT 1990
SPULLER OUTFLOW
SNOWMELT 1992
SPULLER OUTFLOW
SNOWMELT 1991
SPULLER OUTFLOW
SNOWMELT 1993
NITRATE (μEq L⁻¹)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP
0
5
10
15
20
25

Figure I-59



TOPAZ OUTFLOW
SNOWMELT 1990
TOPAZ OUTFLOW
SNOWMELT 1992
TOPAZ OUTFLOW
SNOWMELT 1991
TOPAZ OUTFLOW
SNOWMELT 1993
NITRATE (μEq L-1)
DAILY DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-60

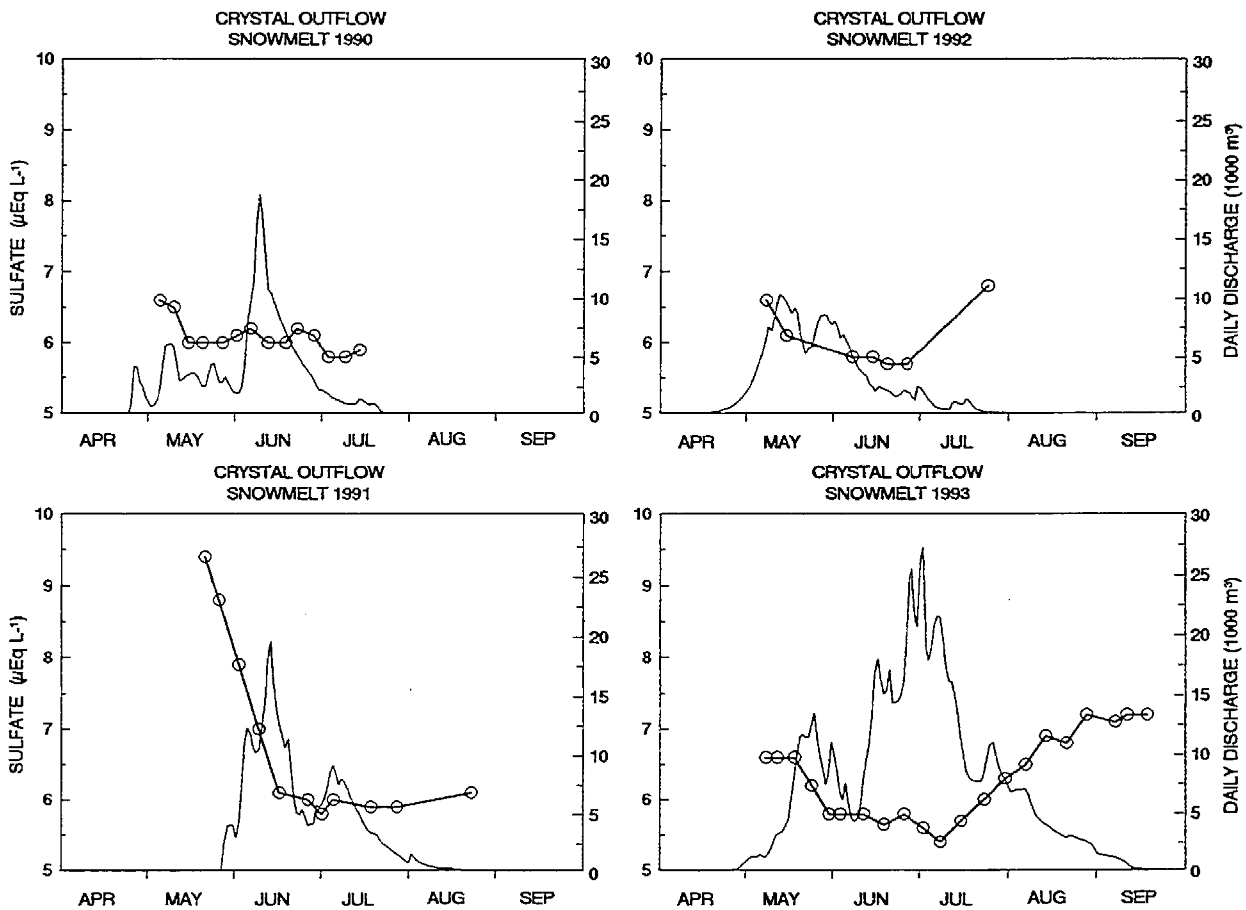

CRYSTAL OUTFLOW
SNOWMELT 1990
CRYSTAL OUTFLOW
SNOWMELT 1992
CRYSTAL OUTFLOW
SNOWMELT 1991
CRYSTAL OUTFLOW
SNOWMELT 1993
SULFATE (μEq L-1)
DAILY DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-61

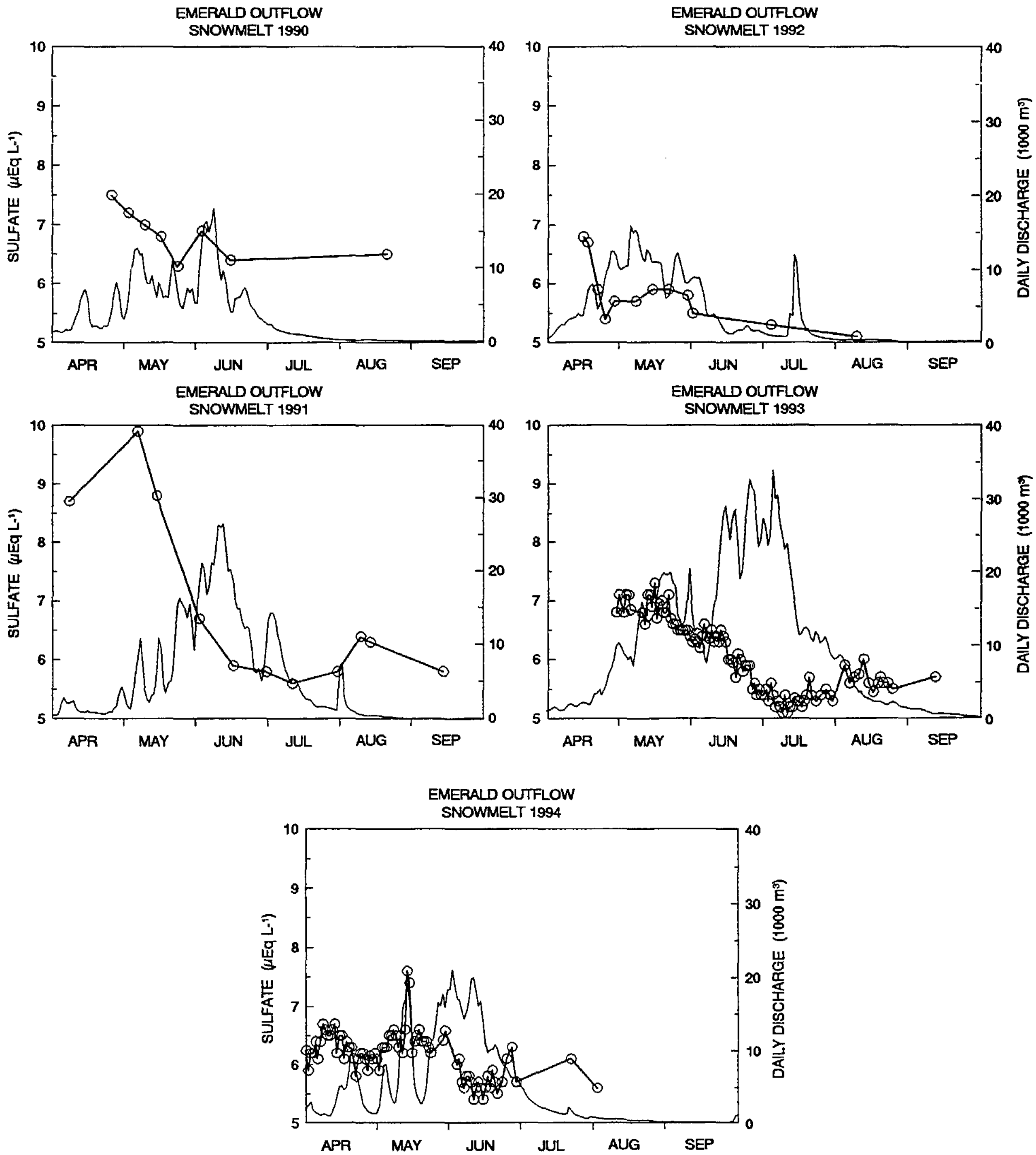

EMERALD OUTFLOW
SNOWMELT 1990
EMERALD OUTFLOW
SNOWMELT 1992
EMERALD OUTFLOW
SNOWMELT 1991
EMERALD OUTFLOW
SNOWMELT 1993
EMERALD OUTFLOW
SNOWMELT 1994
SULFATE (μEq L-1)
DAILY DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-62

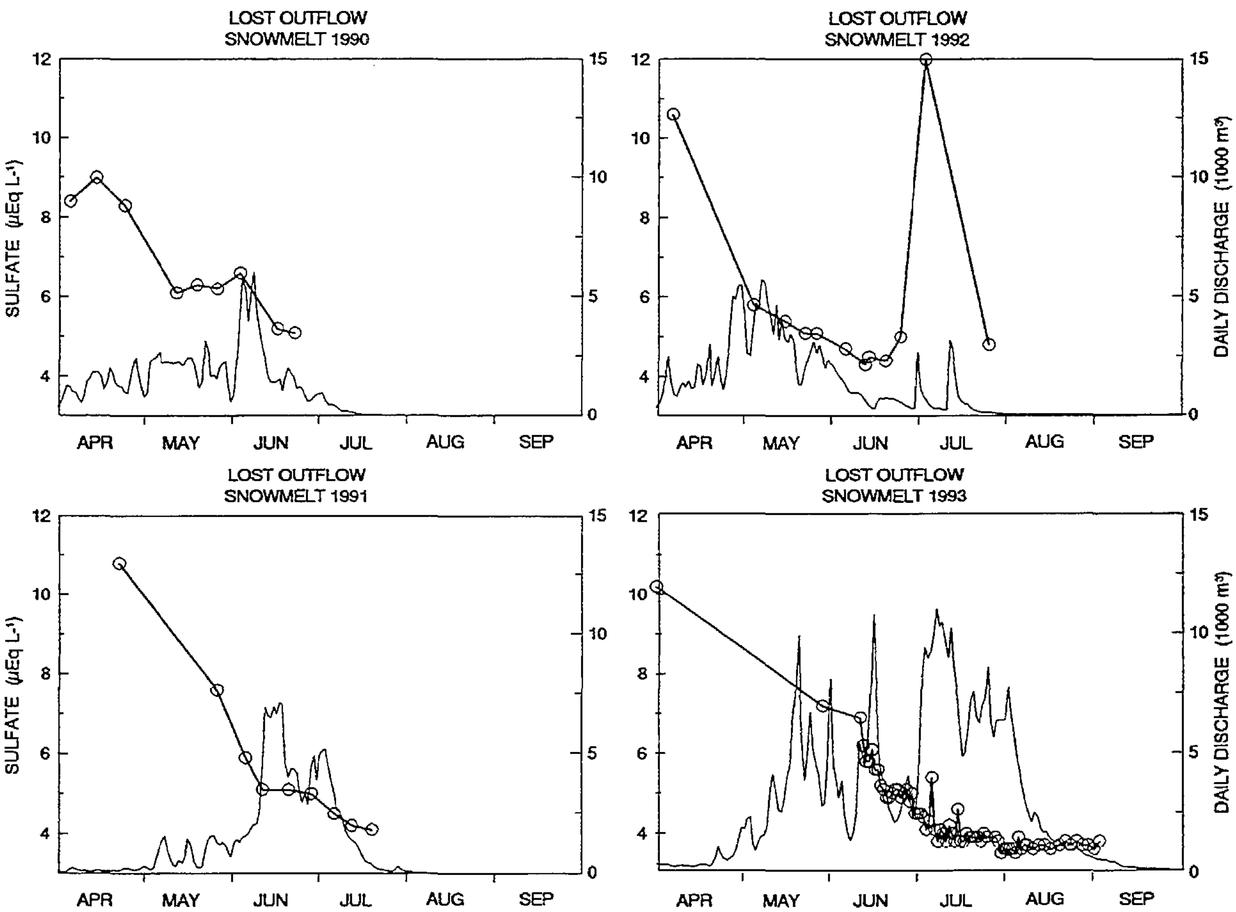

LOST OUTFLOW
SNOWMELT 1990
LOST OUTFLOW
SNOWMELT 1992
LOST OUTFLOW
SNOWMELT 1991
LOST OUTFLOW
SNOWMELT 1993
SULFATE (µEq L-1)
DAILY DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-63

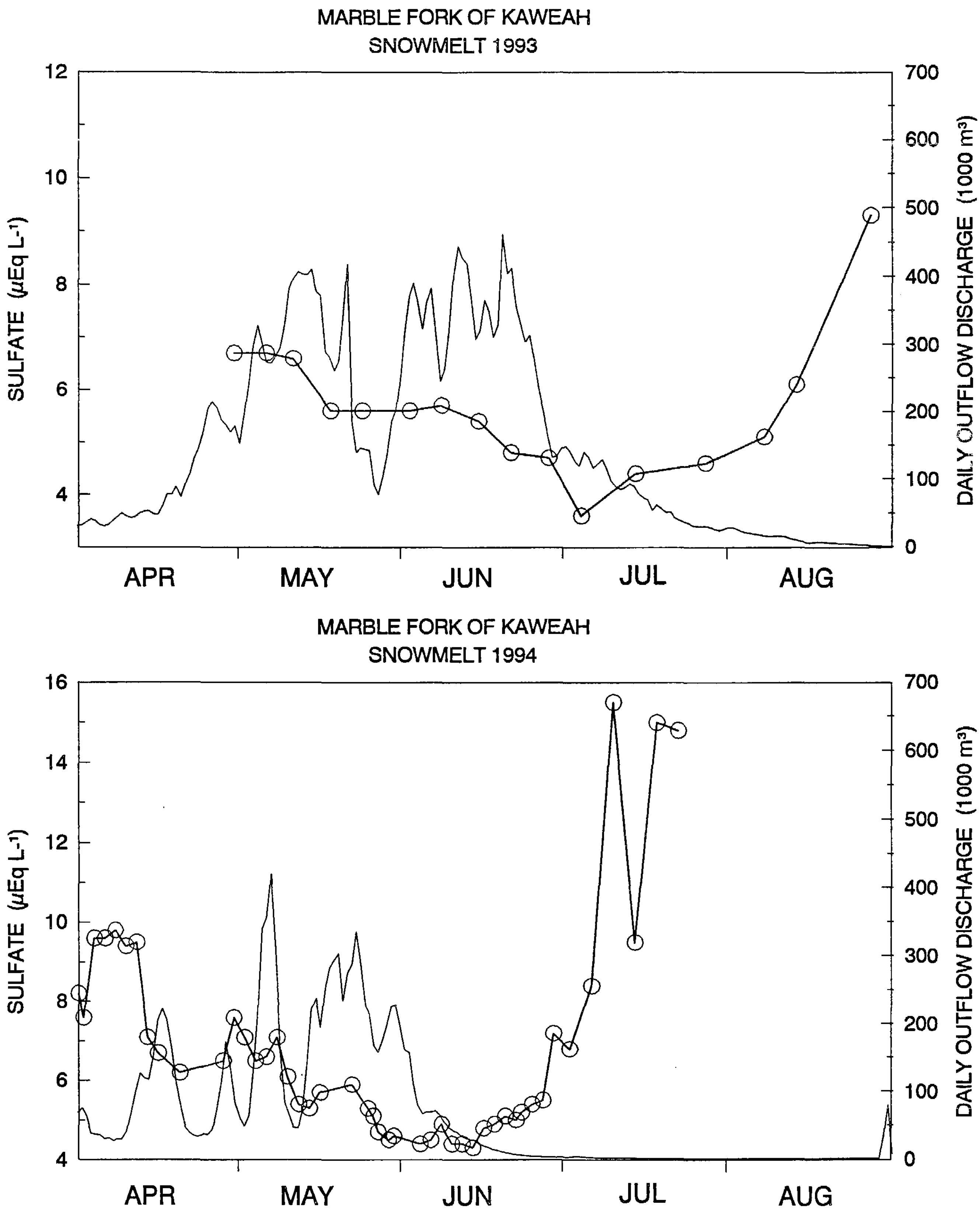

MARBLE FORK OF KAWEAH
SNOWMELT 1993
SULFATE (µEq L-1)
DAILY OUTFLOW DISCHARGE (1000 m3)
12
10
8
6
4
700
600
500
400
300
200
100
0
APR
MAY
JUN
JUL
AUG
MARBLE FORK OF KAWEAH
SNOWMELT 1994
SULFATE (µEq L-1)
DAILY OUTFLOW DISCHARGE (1000 m3)
16
14
12
10
8
6
4
700
600
500
400
300
200
100
0
APR
MAY
JUN
JUL
AUG

Figure I-64

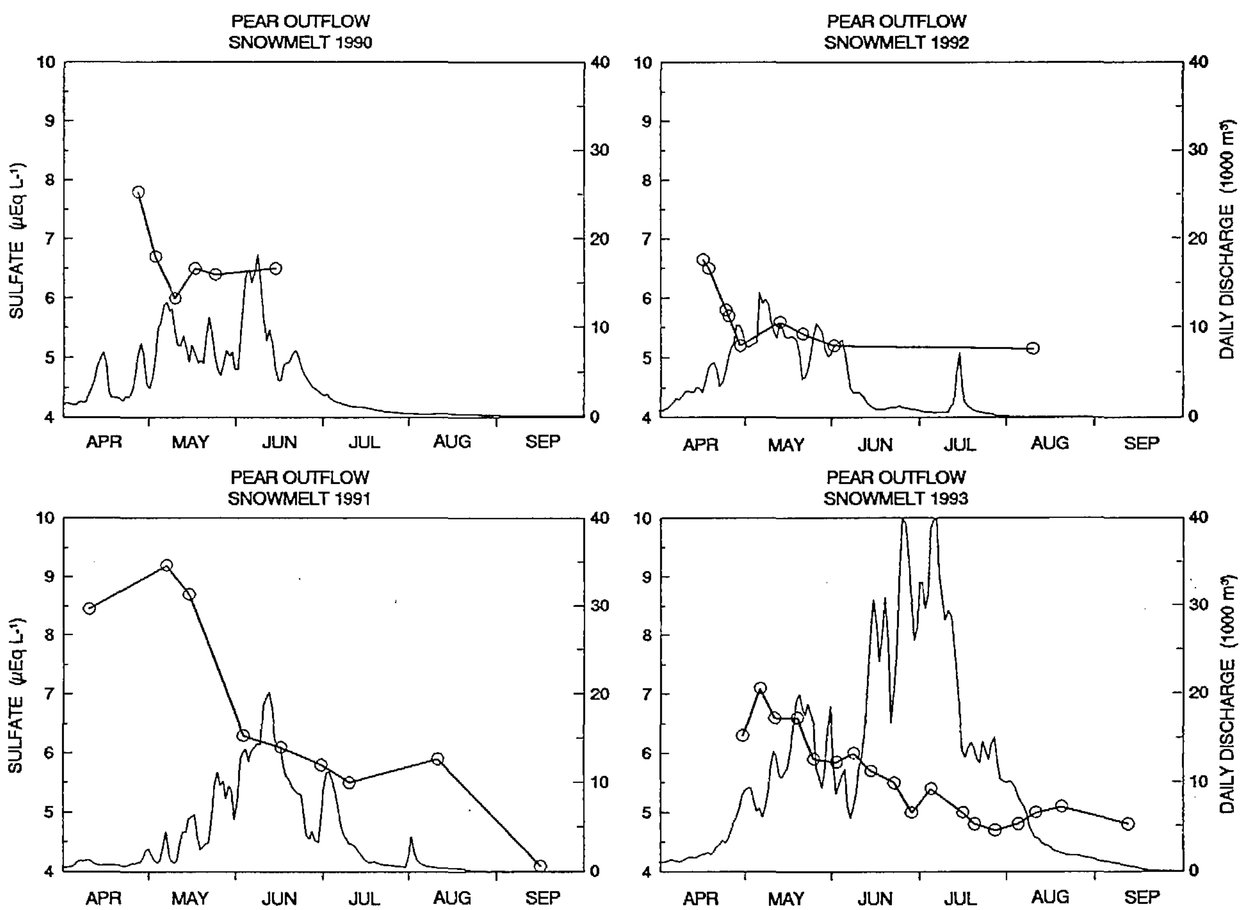

PEAR OUTFLOW
SNOWMELT 1990
PEAR OUTFLOW
SNOWMELT 1992
PEAR OUTFLOW
SNOWMELT 1991
PEAR OUTFLOW
SNOWMELT 1993
SULFATE (μEq L-1)
DAILY DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP
10
9
8
7
6
5
4
40
30
20
10
0

Figure I-65

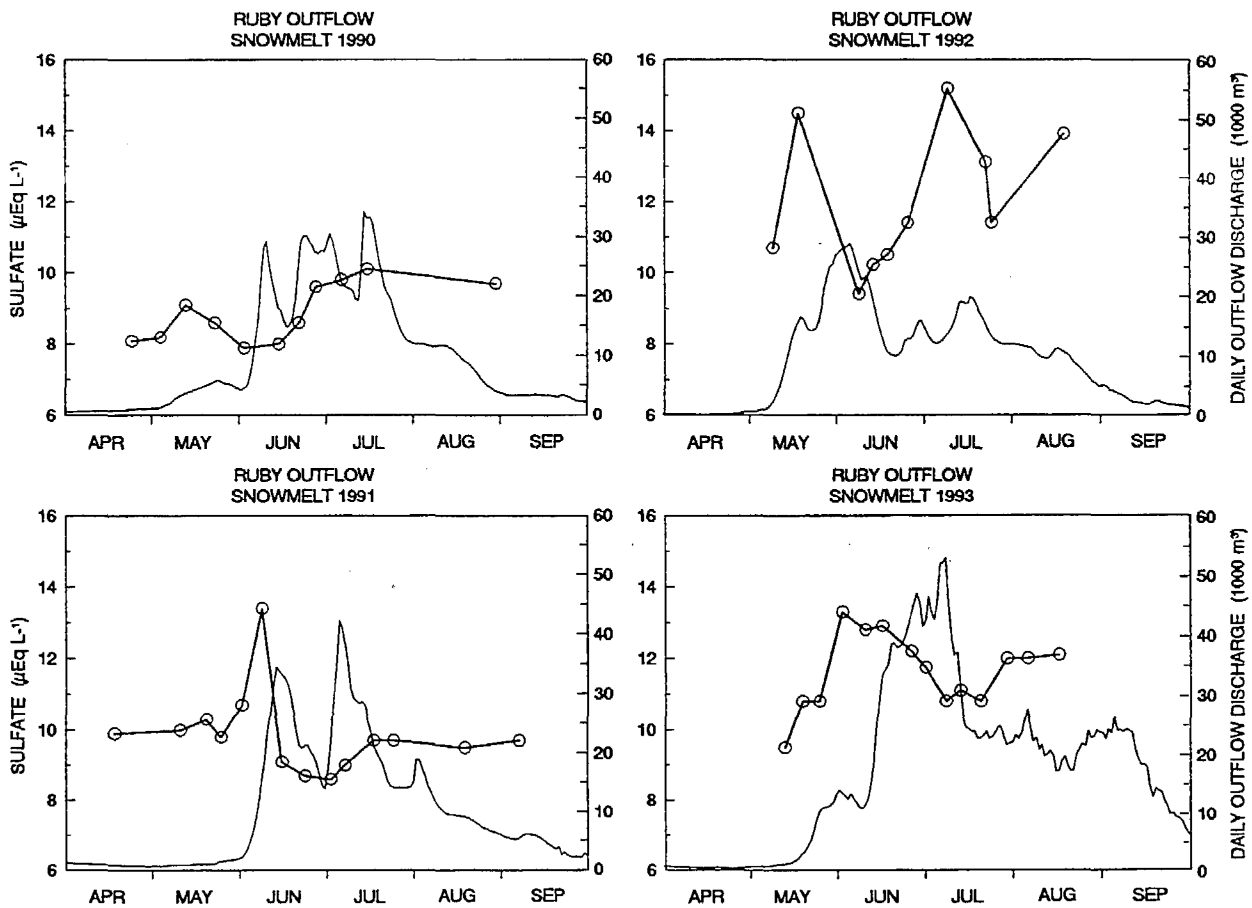

RUBY OUTFLOW
SNOWMELT 1990
RUBY OUTFLOW
SNOWMELT 1992
RUBY OUTFLOW
SNOWMELT 1991
RUBY OUTFLOW
SNOWMELT 1993
SULFATE (μEq L⁻¹)
DAILY OUTFLOW DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP
6
8
10
12
14
16
0
10
20
30
40
50
60

Figure I-66

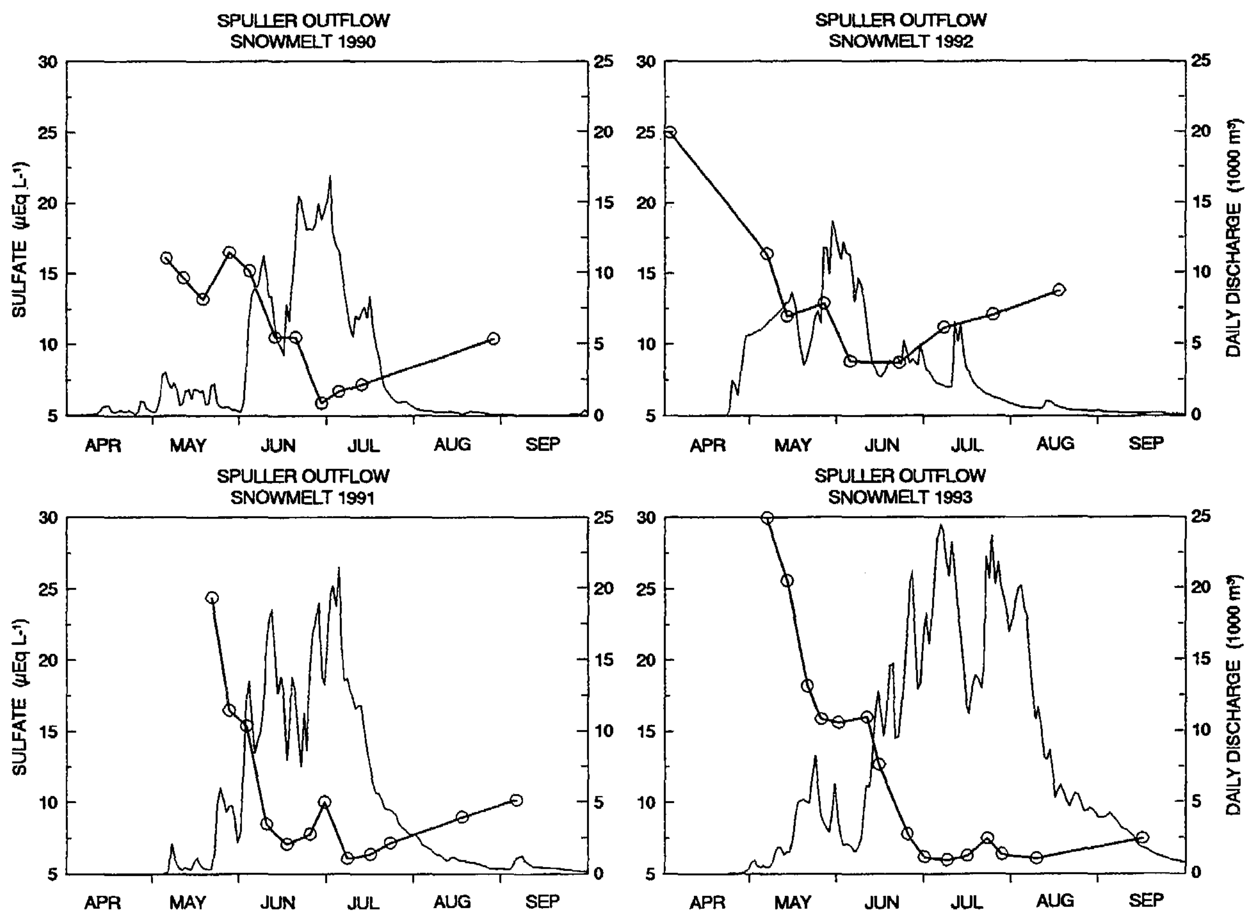

SPULLER OUTFLOW
SNOWMELT 1990
SPULLER OUTFLOW
SNOWMELT 1992
SPULLER OUTFLOW
SNOWMELT 1991
SPULLER OUTFLOW
SNOWMELT 1993
SULFATE (μEq L-1)
DAILY DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP
30
25
20
15
10
5
0

Figure I-67

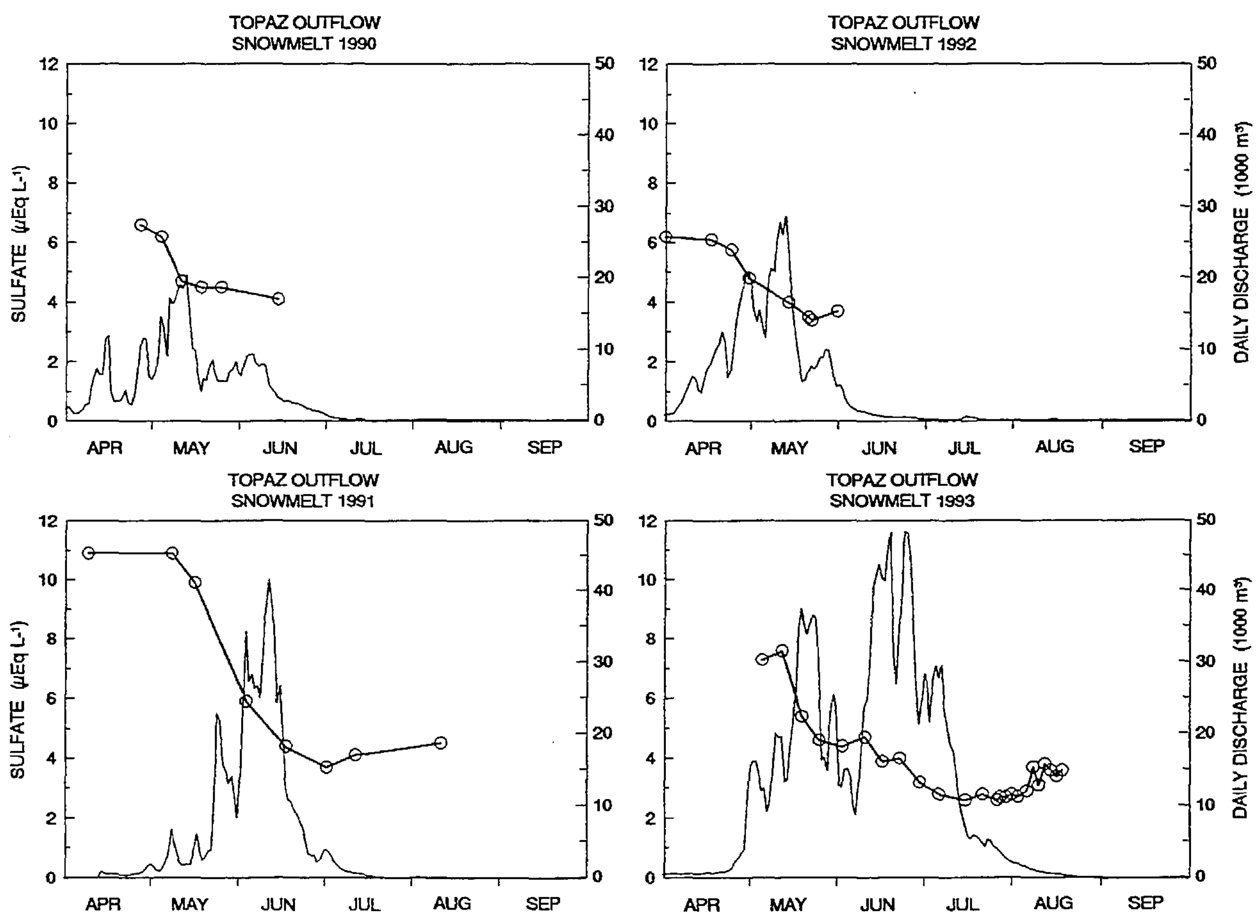

TOPAZ OUTFLOW
SNOWMELT 1990
TOPAZ OUTFLOW
SNOWMELT 1992
TOPAZ OUTFLOW
SNOWMELT 1991
TOPAZ OUTFLOW
SNOWMELT 1993
SULFATE (µEq L⁻¹)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-68

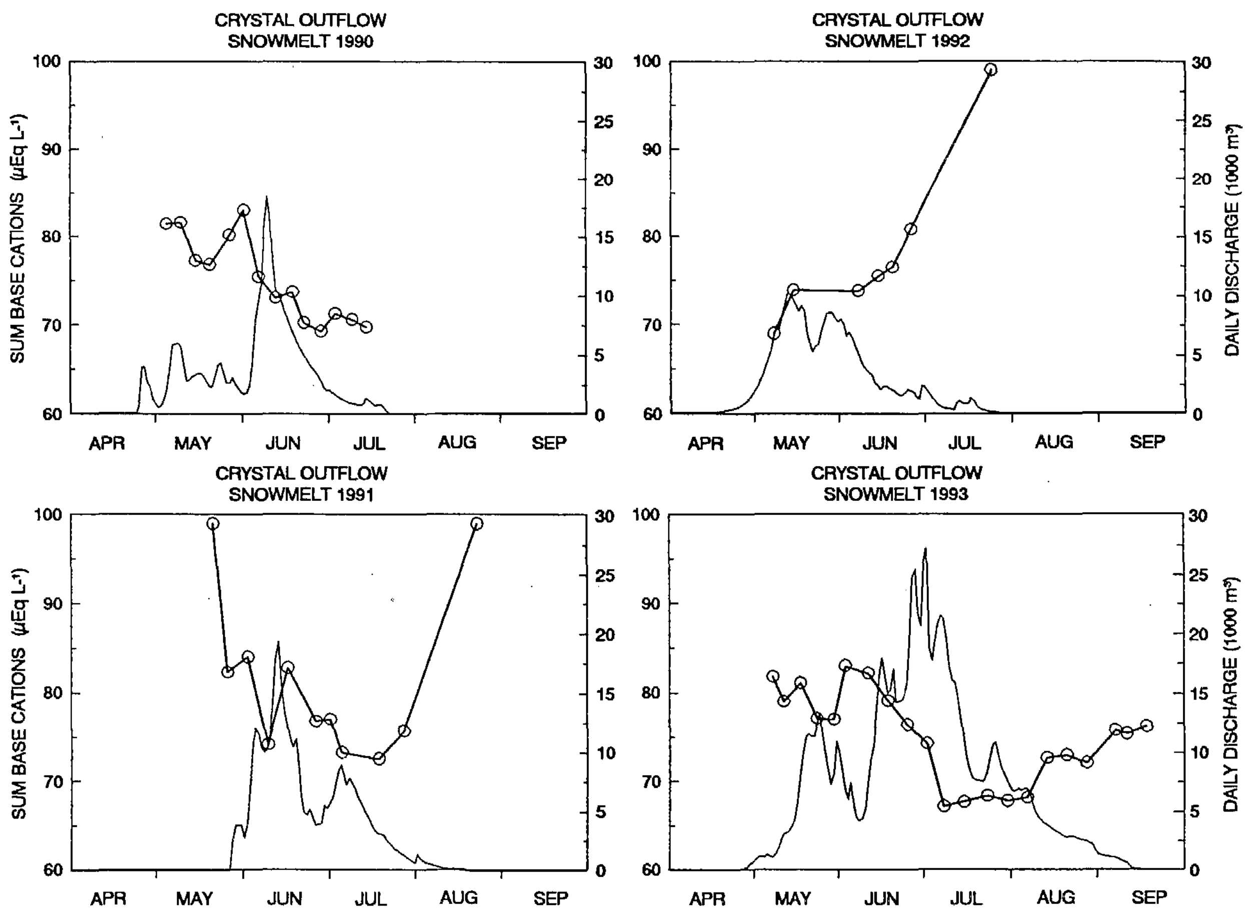
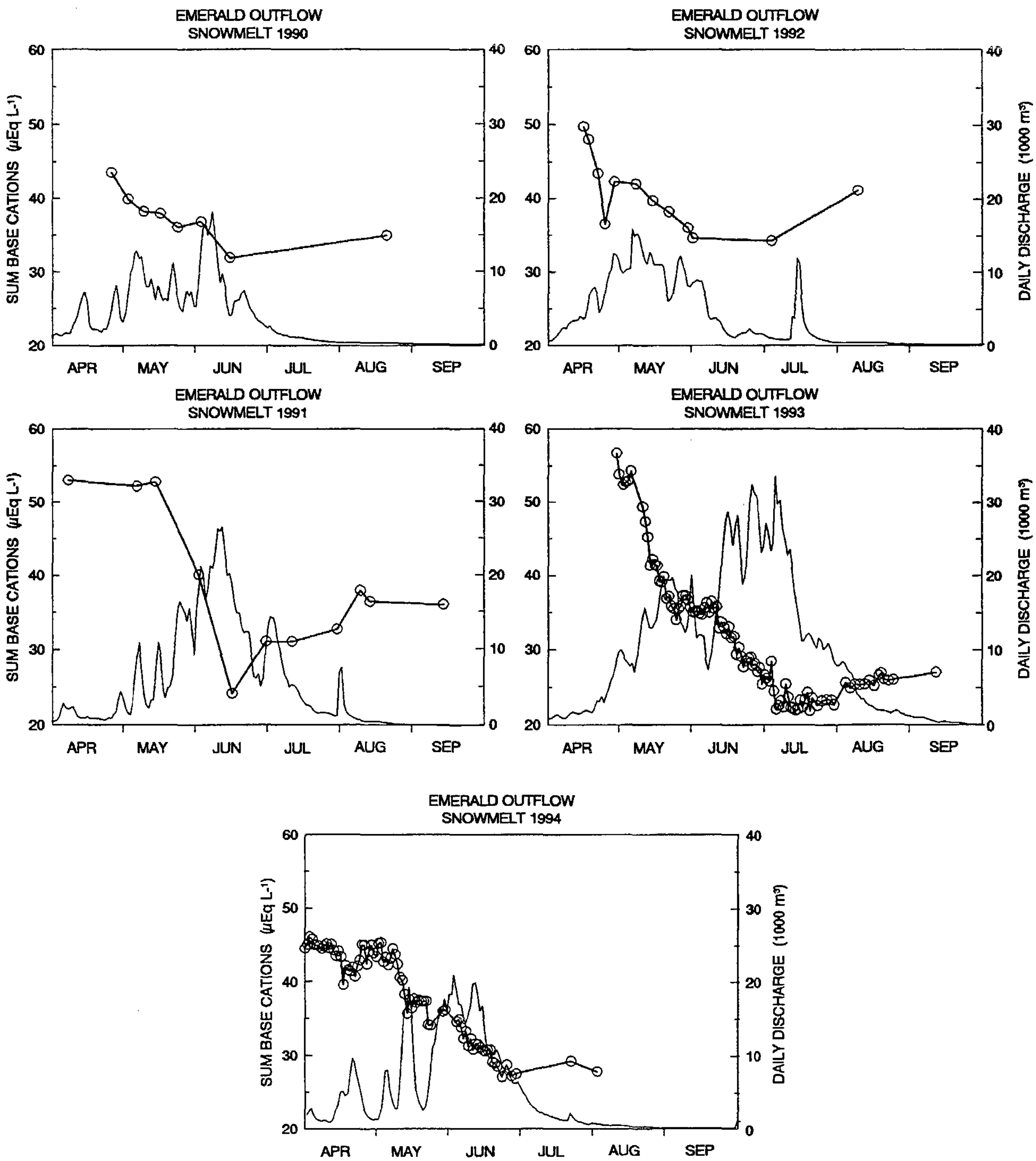
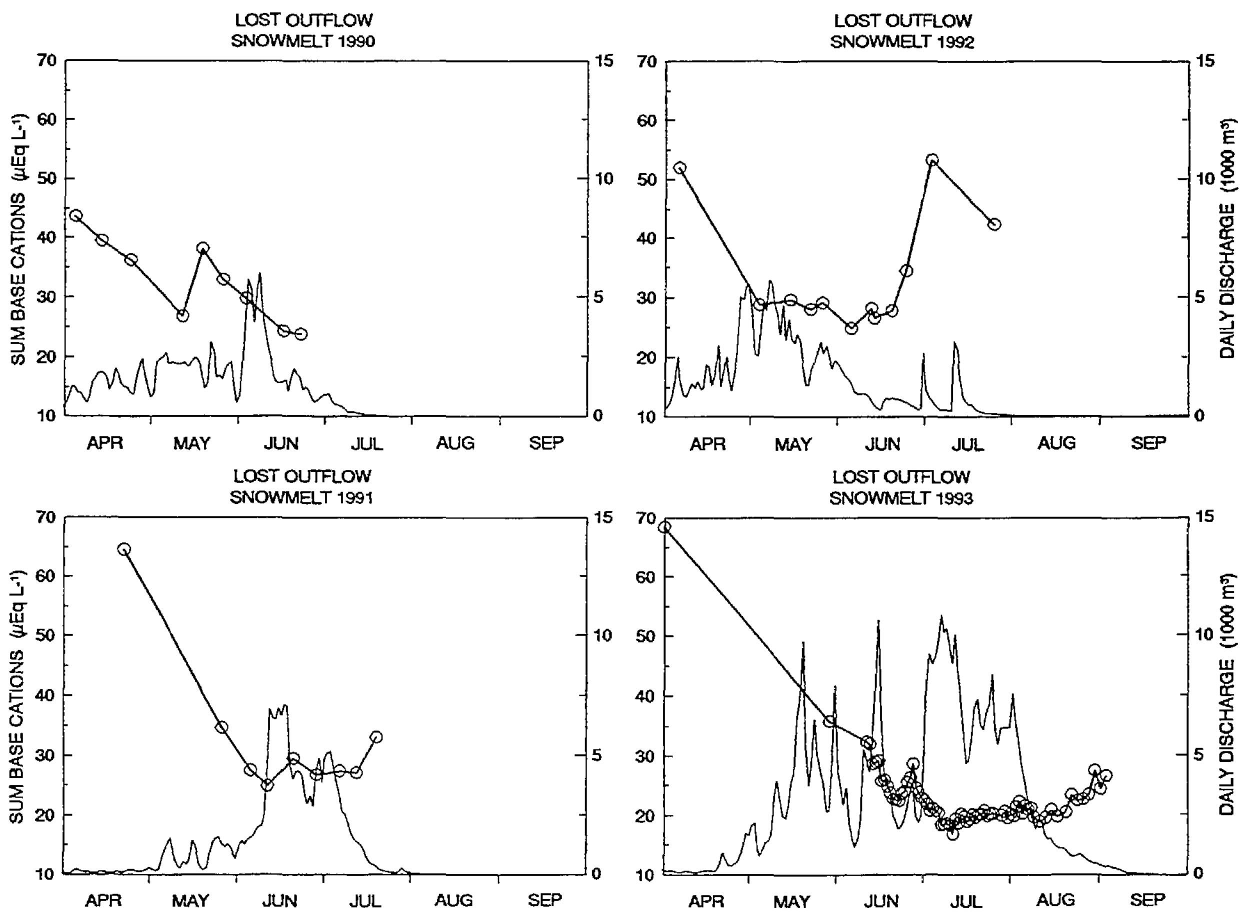

CRYSTAL OUTFLOW
SNOWMELT 1990
CRYSTAL OUTFLOW
SNOWMELT 1992
CRYSTAL OUTFLOW
SNOWMELT 1991
CRYSTAL OUTFLOW
SNOWMELT 1993
SUM BASE CATIONS (μEq L⁻¹)
DAILY DISCHARGE (1000 m³)
100
90
80
70
60
30
25
20
15
10
5
0
APR
MAY
JUN
JUL
AUG
SEP

Figure I-69



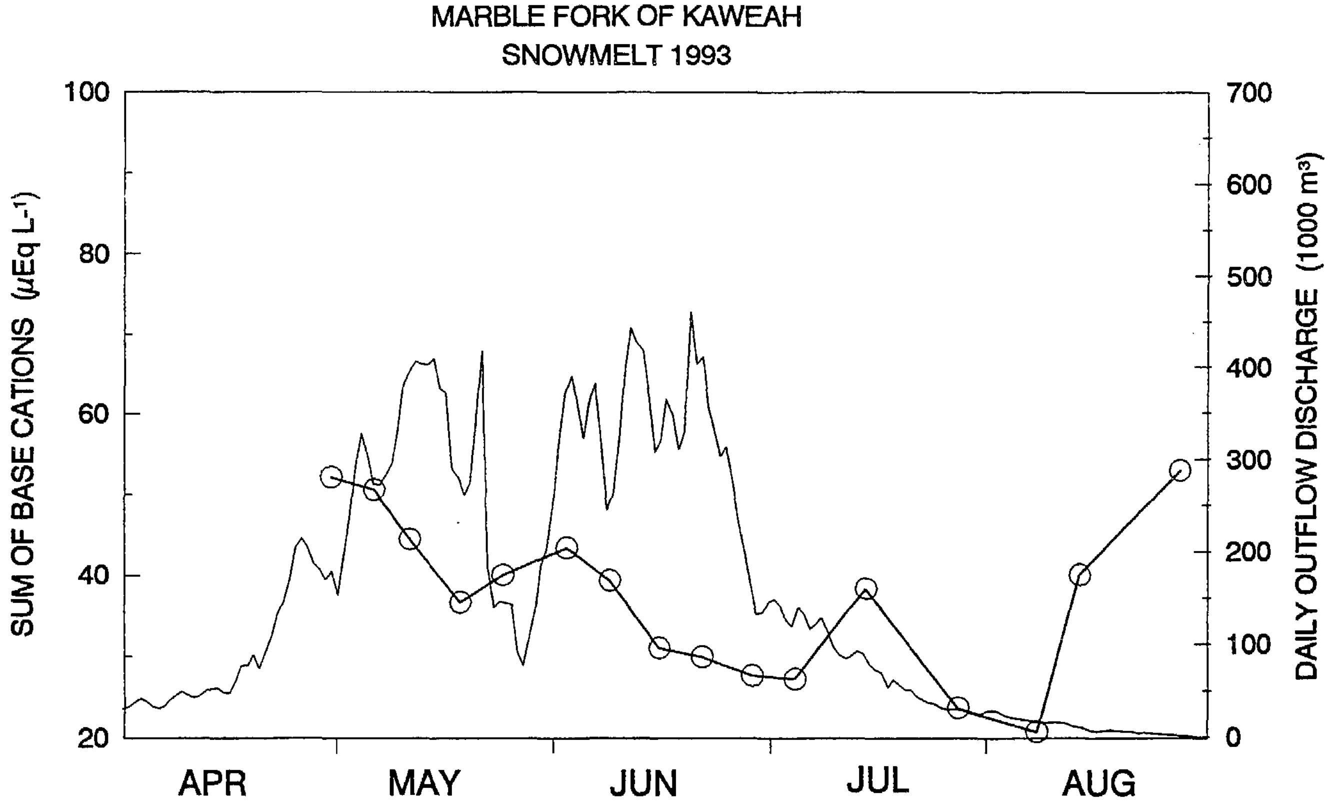
EMERALD OUTFLOW
SNOWMELT 1990
EMERALD OUTFLOW
SNOWMELT 1992
EMERALD OUTFLOW
SNOWMELT 1991
EMERALD OUTFLOW
SNOWMELT 1993
EMERALD OUTFLOW
SNOWMELT 1994
SUM BASE CATIONS (µEq L-1)
DAILY DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-70



LOST OUTFLOW
SNOWMELT 1990
LOST OUTFLOW
SNOWMELT 1992
LOST OUTFLOW
SNOWMELT 1991
LOST OUTFLOW
SNOWMELT 1993
SUM BASE CATIONS (μEq L^{-1})
DAILY DISCHARGE (1000 m^3)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-71


MARBLE FORK OF KAWEAH
SNOWMELT 1993
SUM OF BASE CATIONS (μEq L^{-1})
DAILY OUTFLOW DISCHARGE (1000 m^3)
100
80
60
40
20
700
600
500
400
300
200
100
0
APR
MAY
JUN
JUL
AUG

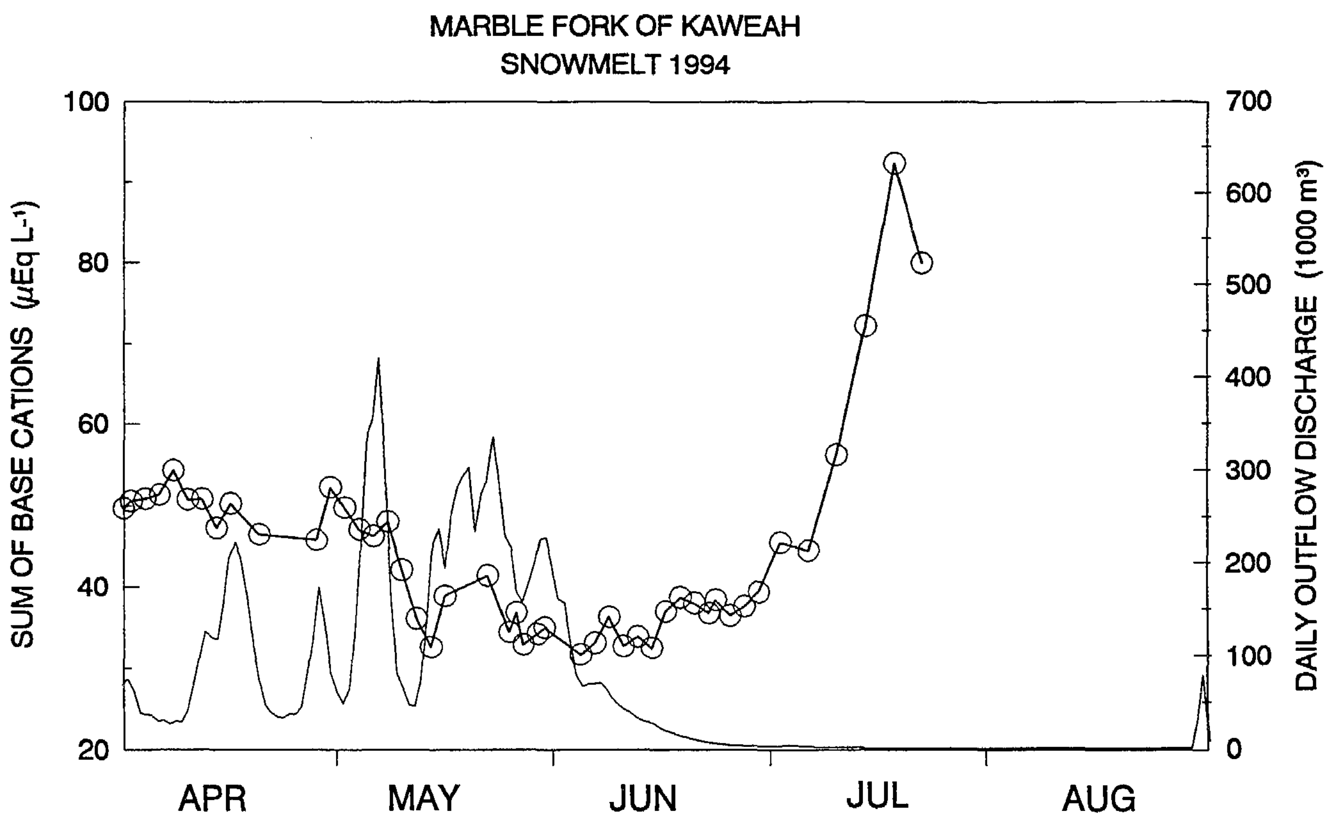

MARBLE FORK OF KAWEAH
SNOWMELT 1994
SUM OF BASE CATIONS (μEq L^{-1})
DAILY OUTFLOW DISCHARGE (1000 m^3)
100
80
60
40
20
700
600
500
400
300
200
100
0
APR
MAY
JUN
JUL
AUG

Figure I-72

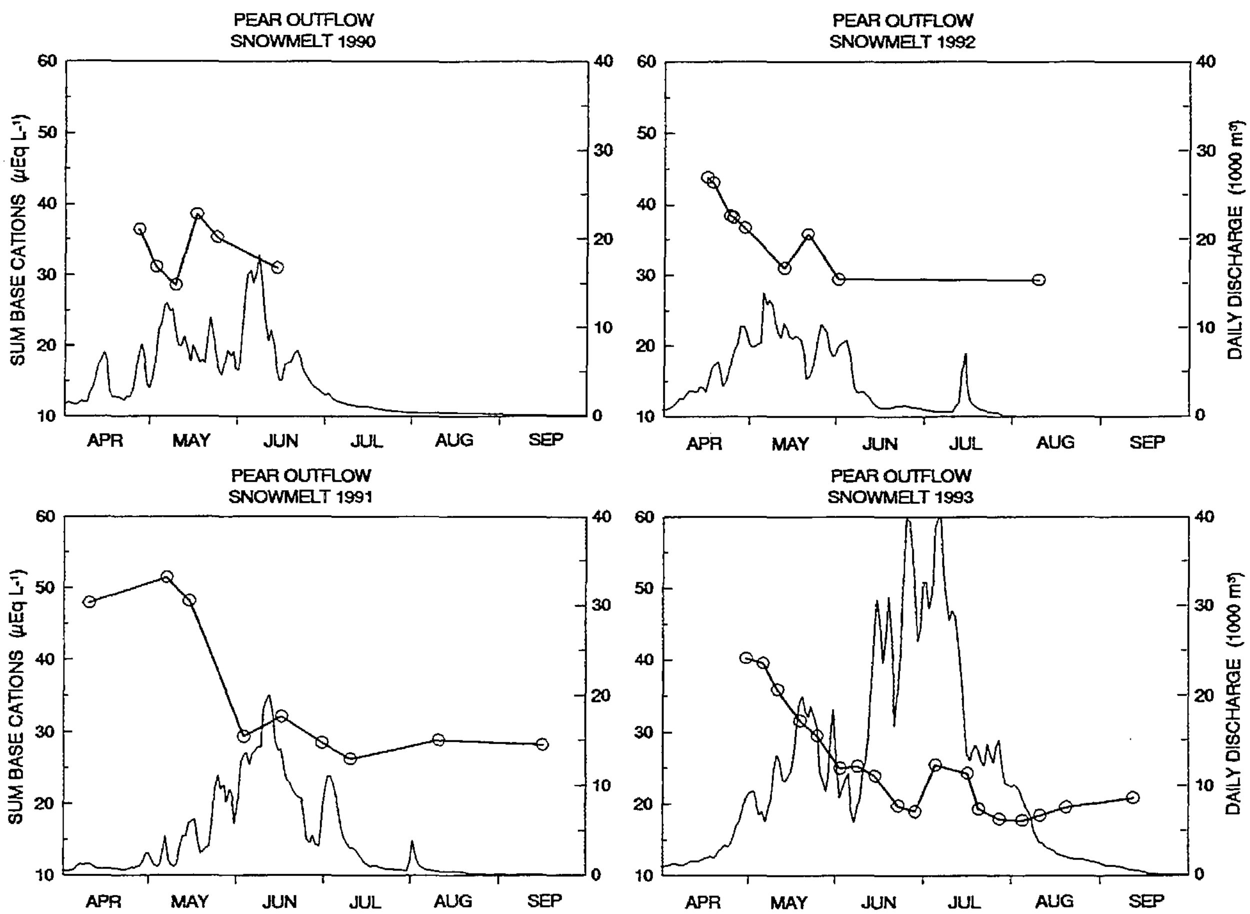
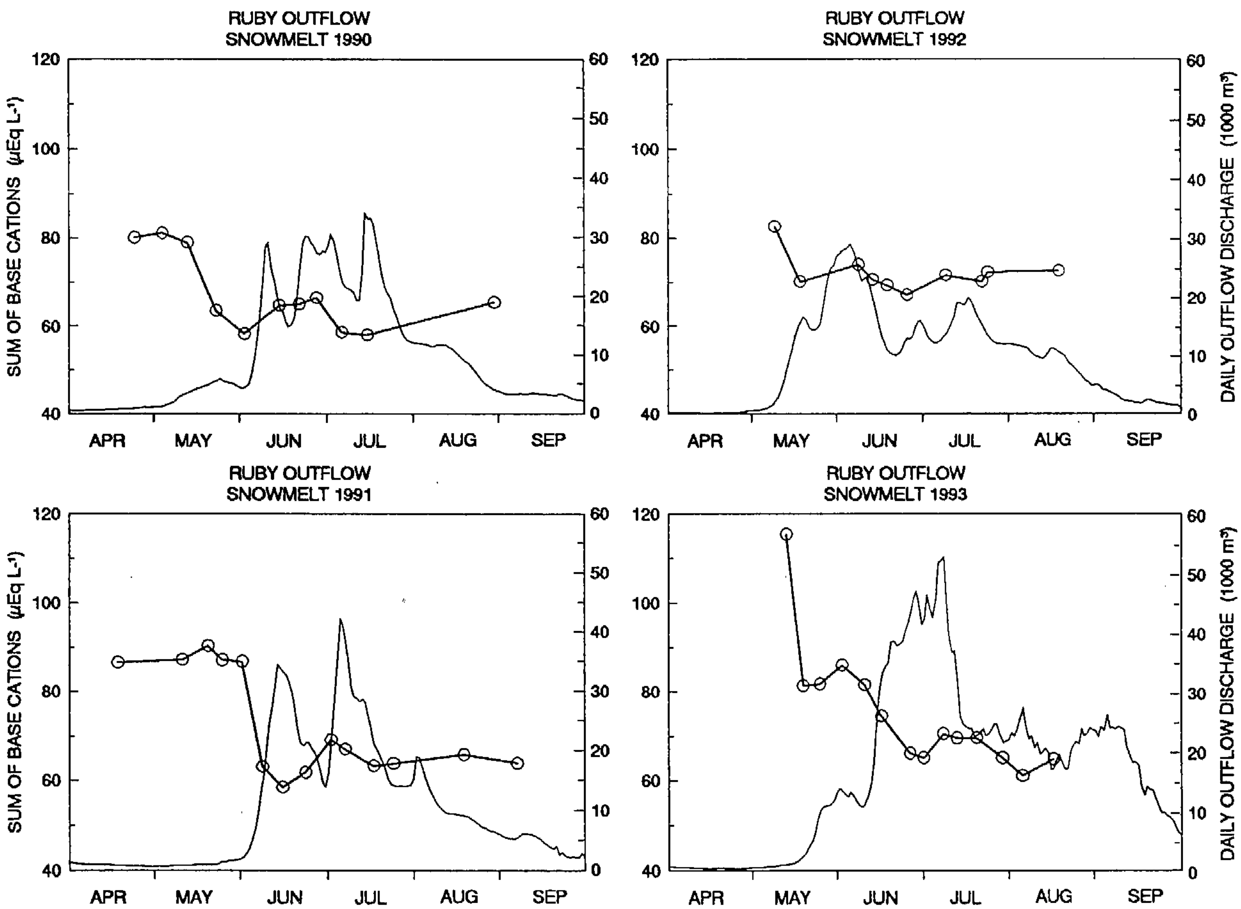

PEAR OUTFLOW
SNOWMELT 1990
PEAR OUTFLOW
SNOWMELT 1992
PEAR OUTFLOW
SNOWMELT 1991
PEAR OUTFLOW
SNOWMELT 1993
SUM BASE CATIONS (μEq L-1)
DAILY DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-73



RUBY OUTFLOW
SNOWMELT 1990
RUBY OUTFLOW
SNOWMELT 1992
RUBY OUTFLOW
SNOWMELT 1991
RUBY OUTFLOW
SNOWMELT 1993
SUM OF BASE CATIONS (μEq L-1)
DAILY OUTFLOW DISCHARGE (1000 m3)
APR
MAY
JUN
JUL
AUG
SEP
120
100
80
60
40
60
50
40
30
20
10
0

Figure I-74

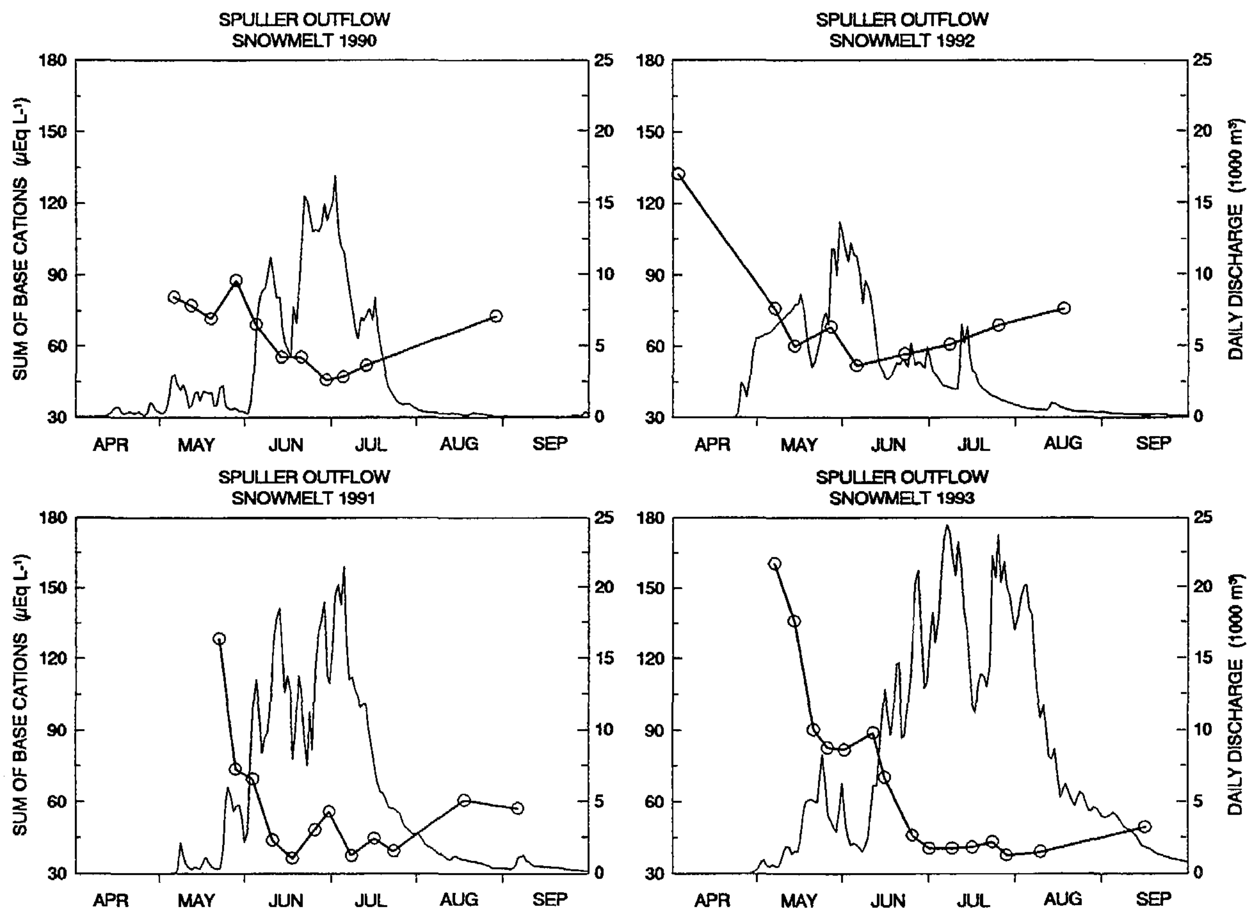

SPULLER OUTFLOW
SNOWMELT 1990
SPULLER OUTFLOW
SNOWMELT 1992
SPULLER OUTFLOW
SNOWMELT 1991
SPULLER OUTFLOW
SNOWMELT 1993
SUM OF BASE CATIONS (μEq L-1)
DAILY DISCHARGE (1000 m3)
180
150
120
90
60
30
25
20
15
10
5
0
APR
MAY
JUN
JUL
AUG
SEP

Figure I-75

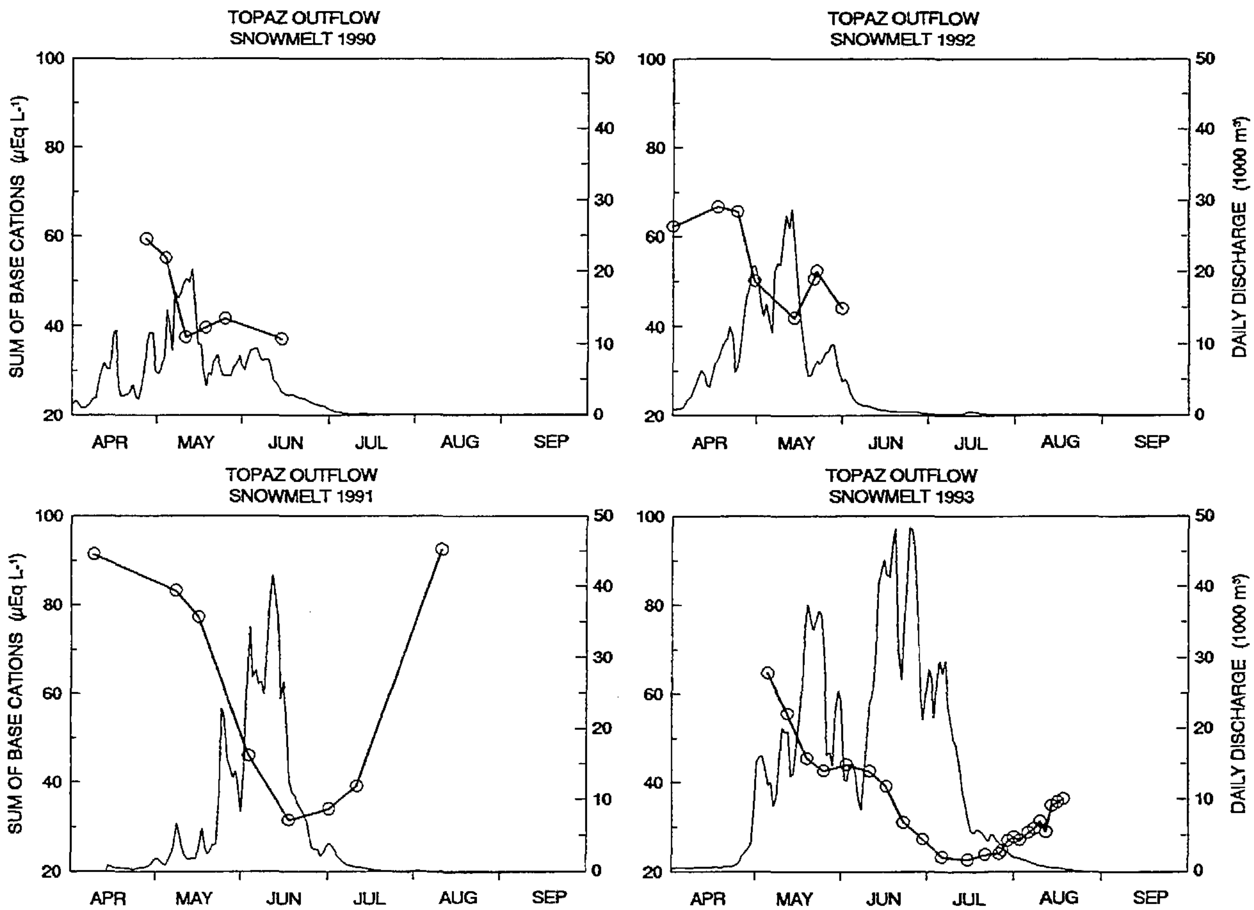

TOPAZ OUTFLOW
SNOWMELT 1990
TOPAZ OUTFLOW
SNOWMELT 1992
TOPAZ OUTFLOW
SNOWMELT 1991
TOPAZ OUTFLOW
SNOWMELT 1993
SUM OF BASE CATIONS (μEq L-1)
DAILY DISCHARGE (1000 m3)
100
80
60
40
20
50
40
30
20
10
0
APR
MAY
JUN
JUL
AUG
SEP

Figure I-76

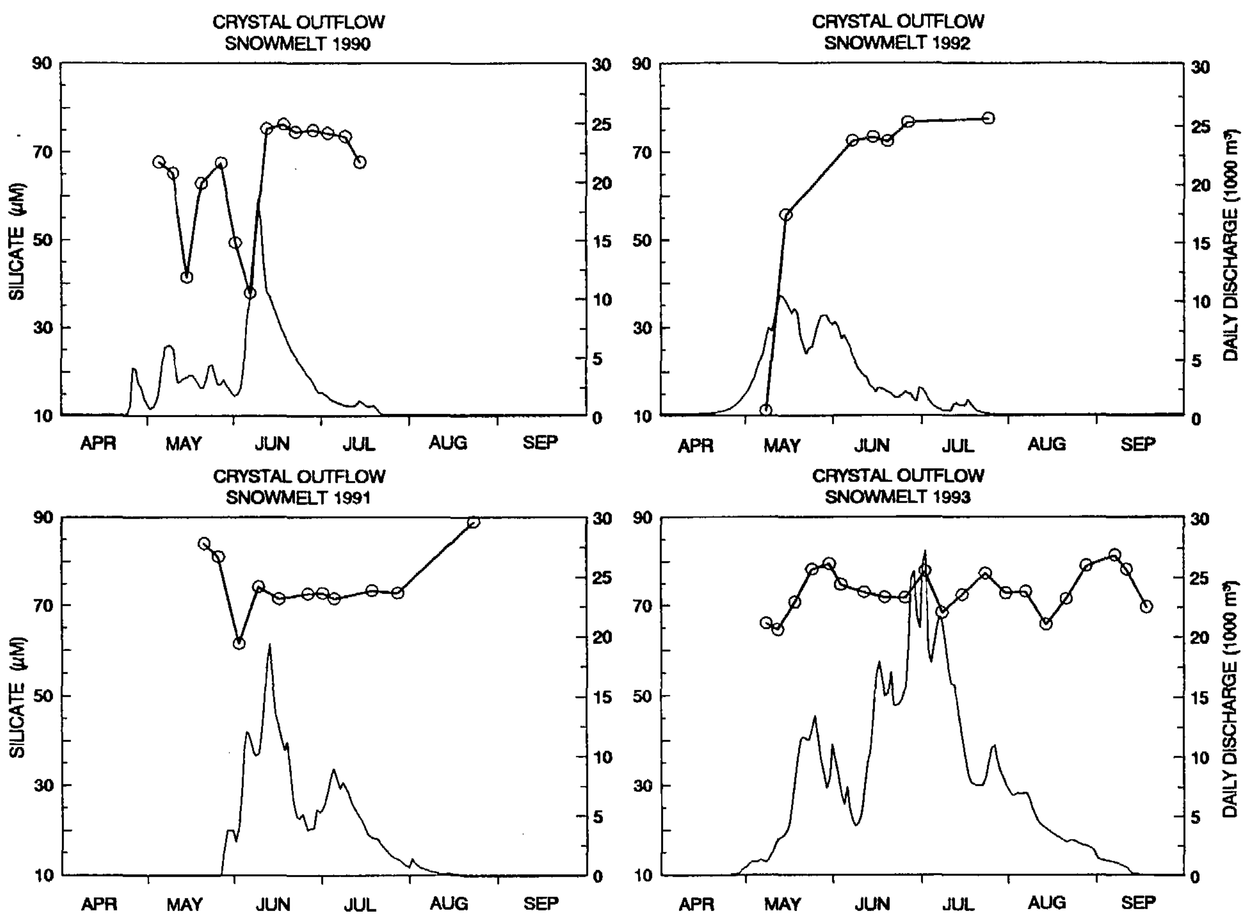

CRYSTAL OUTFLOW
SNOWMELT 1990
CRYSTAL OUTFLOW
SNOWMELT 1992
CRYSTAL OUTFLOW
SNOWMELT 1991
CRYSTAL OUTFLOW
SNOWMELT 1993
SILICATE (µM)
DAILY DISCHARGE (1000 m³)
90
70
50
30
10
30
25
20
15
10
5
0
APR
MAY
JUN
JUL
AUG
SEP

Figure I-77

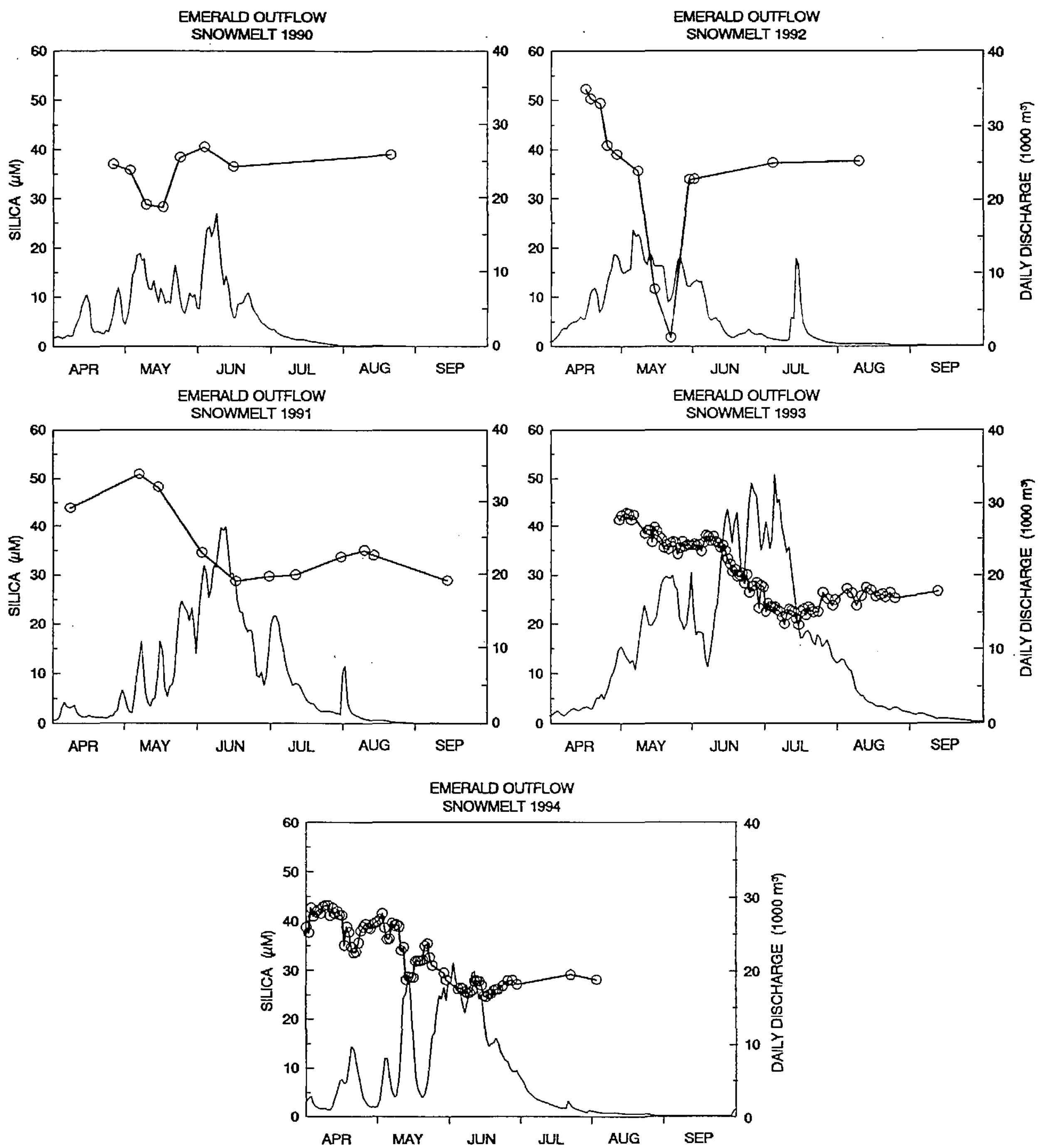

EMERALD OUTFLOW
SNOWMELT 1990
EMERALD OUTFLOW
SNOWMELT 1992
EMERALD OUTFLOW
SNOWMELT 1991
EMERALD OUTFLOW
SNOWMELT 1993
EMERALD OUTFLOW
SNOWMELT 1994
SILICA (µM)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-78

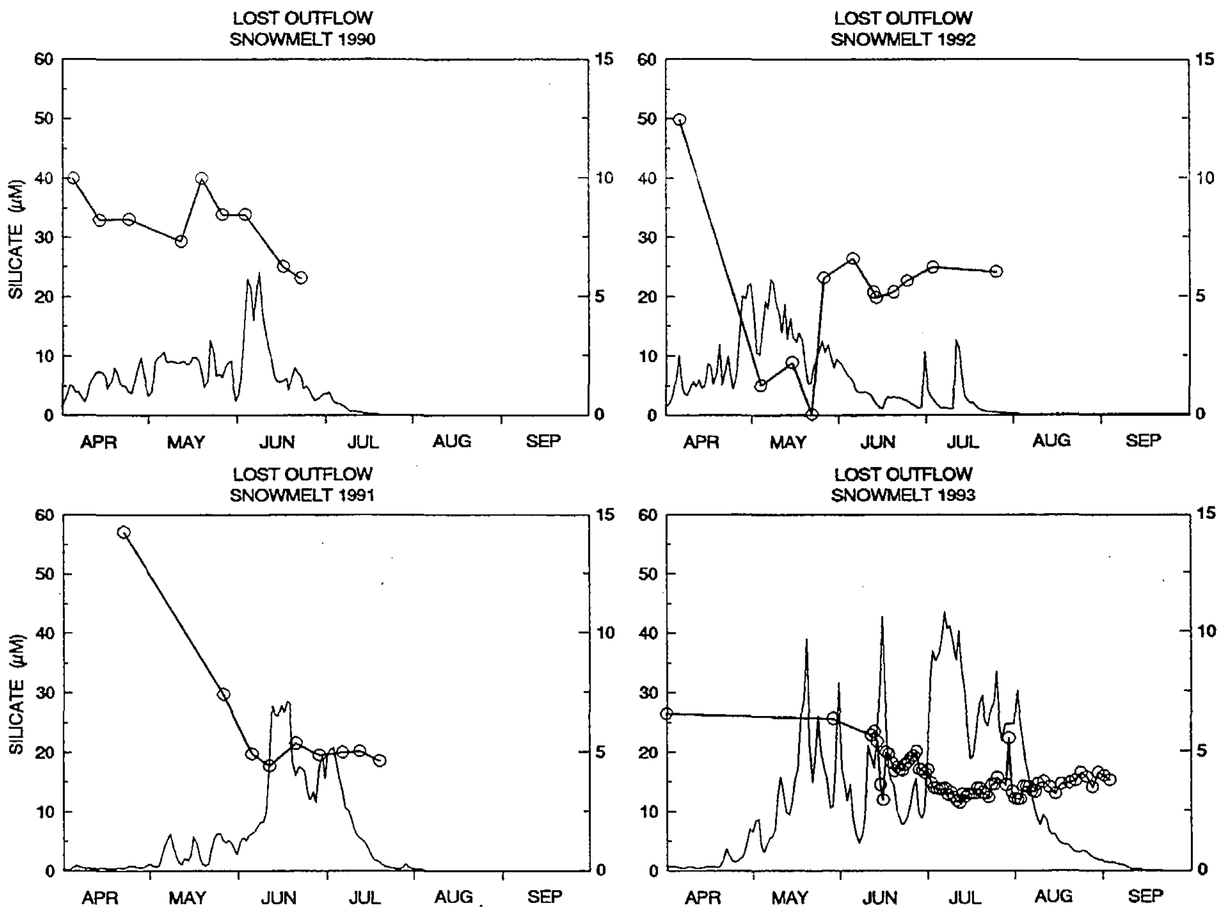
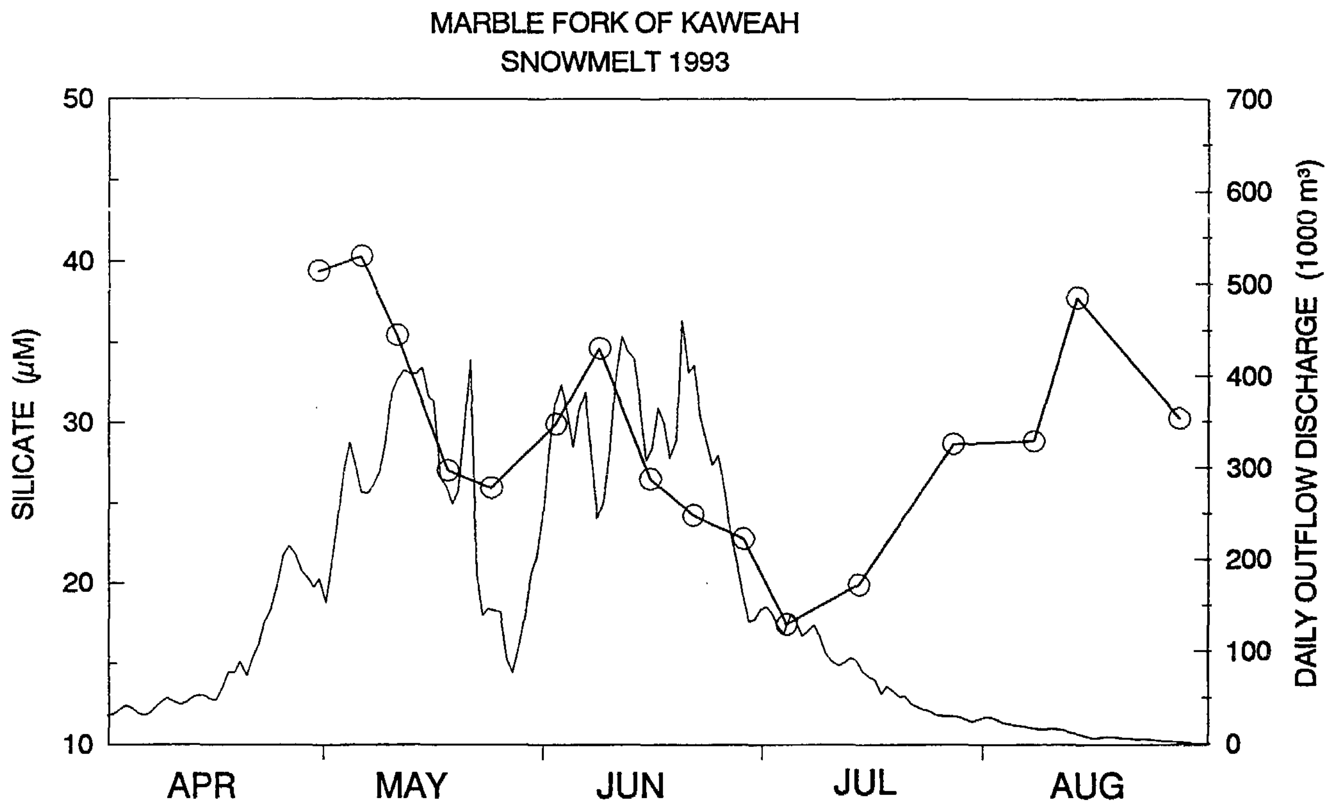

LOST OUTFLOW
SNOWMELT 1990
LOST OUTFLOW
SNOWMELT 1992
LOST OUTFLOW
SNOWMELT 1991
LOST OUTFLOW
SNOWMELT 1993
SILICATE (μM)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP
0
10
20
30
40
50
60
5
15

Figure I-79


MARBLE FORK OF KAWEAH
SNOWMELT 1993
SILICATE (µM)
DAILY OUTFLOW DISCHARGE (1000 m³)
50
40
30
20
10
700
600
500
400
300
200
100
0
APR
MAY
JUN
JUL
AUG

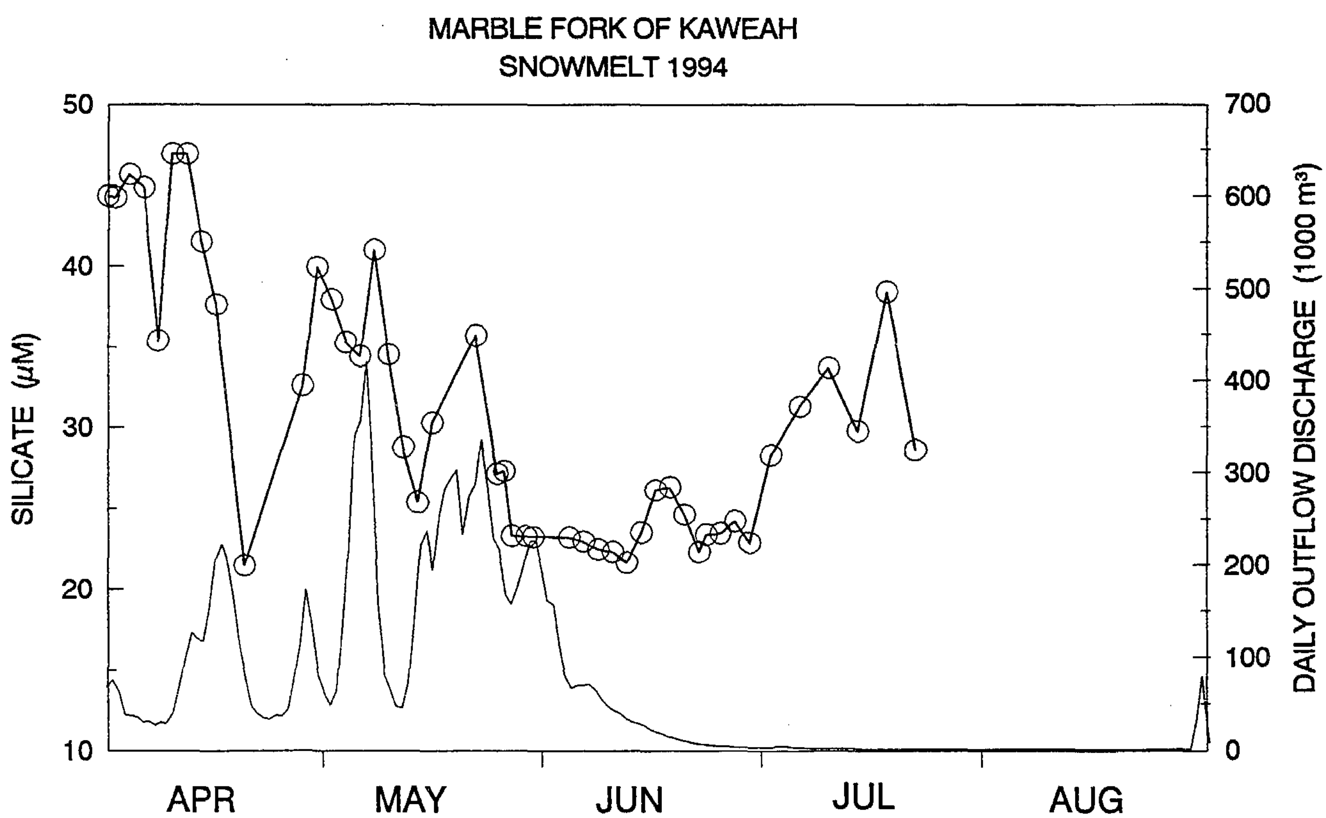
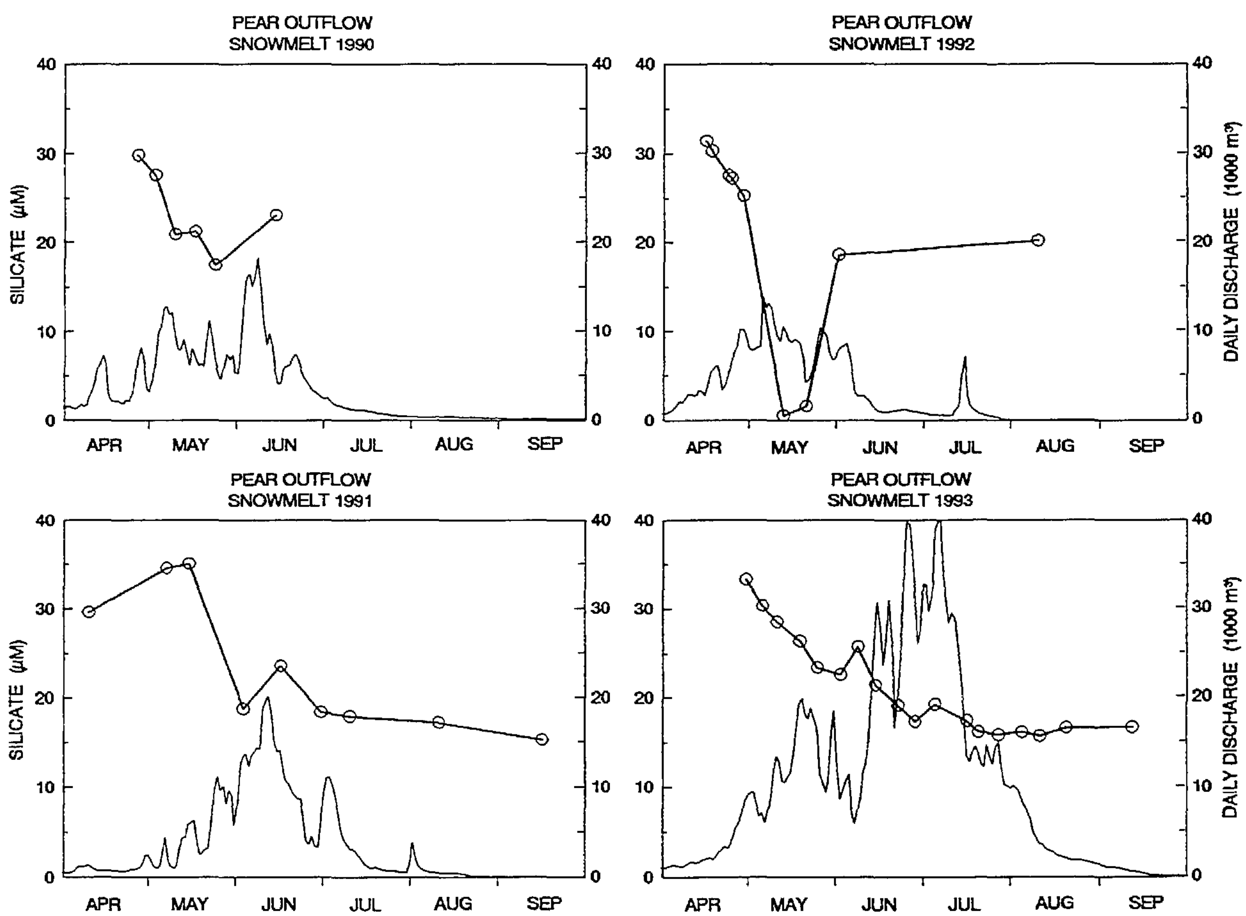

MARBLE FORK OF KAWEAH
SNOWMELT 1994
SILICATE (µM)
DAILY OUTFLOW DISCHARGE (1000 m³)
50
40
30
20
10
700
600
500
400
300
200
100
0
APR
MAY
JUN
JUL
AUG

Figure I-80



PEAR OUTFLOW
SNOWMELT 1990
PEAR OUTFLOW
SNOWMELT 1992
PEAR OUTFLOW
SNOWMELT 1991
PEAR OUTFLOW
SNOWMELT 1993
SILICATE (µM)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP

Figure I-81

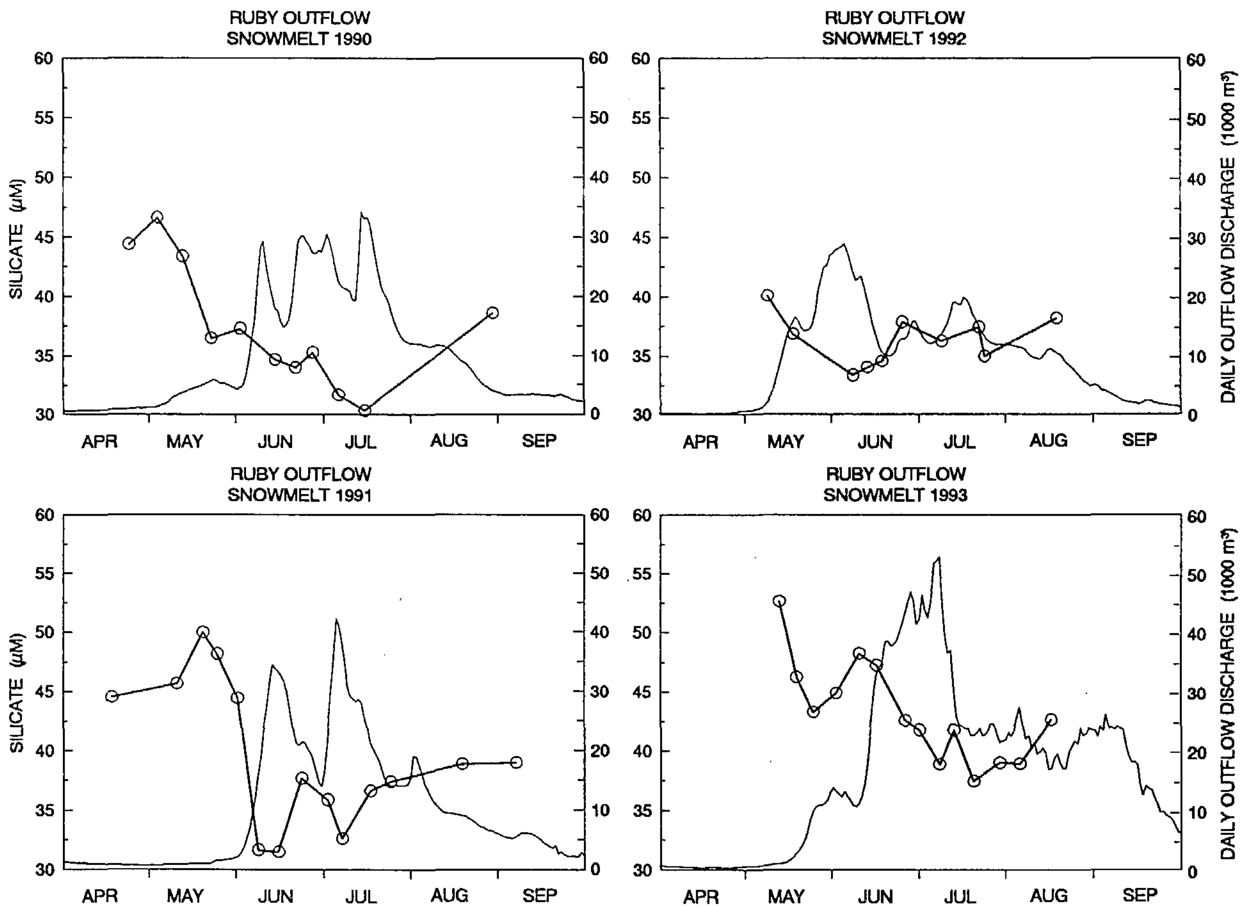

RUBY OUTFLOW
SNOWMELT 1990
RUBY OUTFLOW
SNOWMELT 1992
RUBY OUTFLOW
SNOWMELT 1991
RUBY OUTFLOW
SNOWMELT 1993
SILICATE (μM)
DAILY OUTFLOW DISCHARGE (1000 m³)
60
55
50
45
40
35
30
0
10
20
30
40
50
60
APR
MAY
JUN
JUL
AUG
SEP

Figure I-82

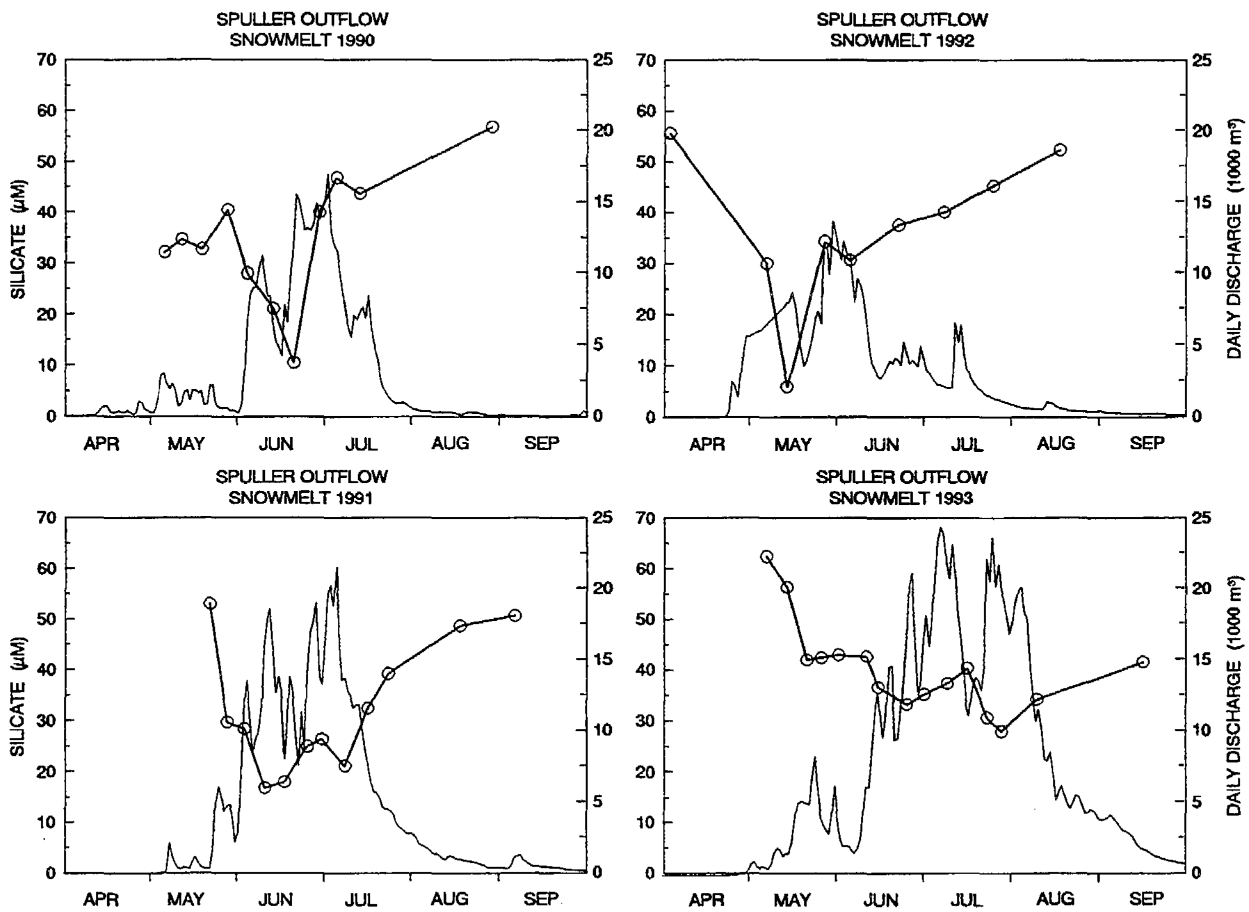
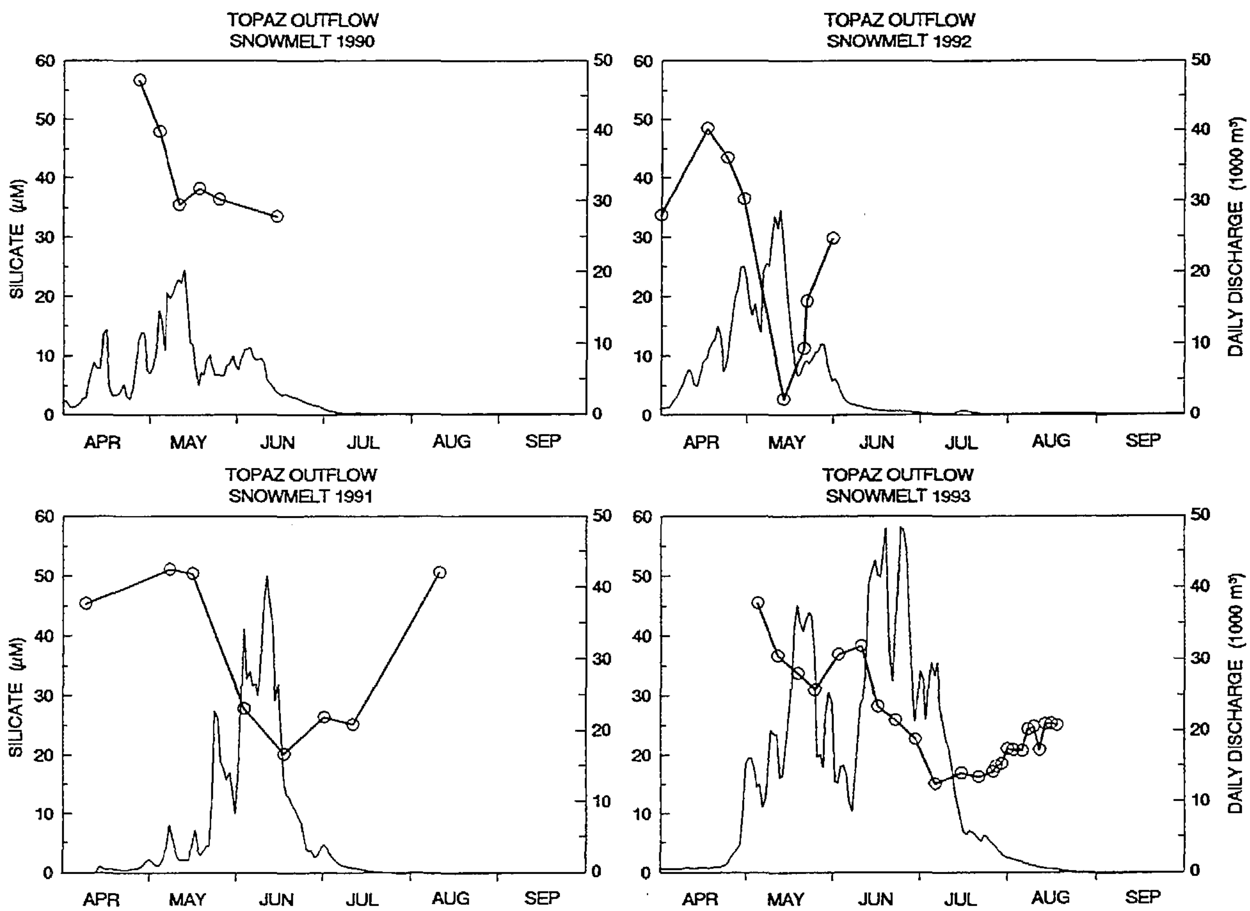

SPULLER OUTFLOW
SNOWMELT 1990
SPULLER OUTFLOW
SNOWMELT 1992
SPULLER OUTFLOW
SNOWMELT 1991
SPULLER OUTFLOW
SNOWMELT 1993
SILICATE (μM)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP
0
10
20
30
40
50
60
70
0
5
10
15
20
25

Figure I-83



TOPAZ OUTFLOW
SNOWMELT 1990
TOPAZ OUTFLOW
SNOWMELT 1992
TOPAZ OUTFLOW
SNOWMELT 1991
TOPAZ OUTFLOW
SNOWMELT 1993
SILICATE (μM)
DAILY DISCHARGE (1000 m³)
APR
MAY
JUN
JUL
AUG
SEP
0
10
20
30
40
50
60

Figure I-84

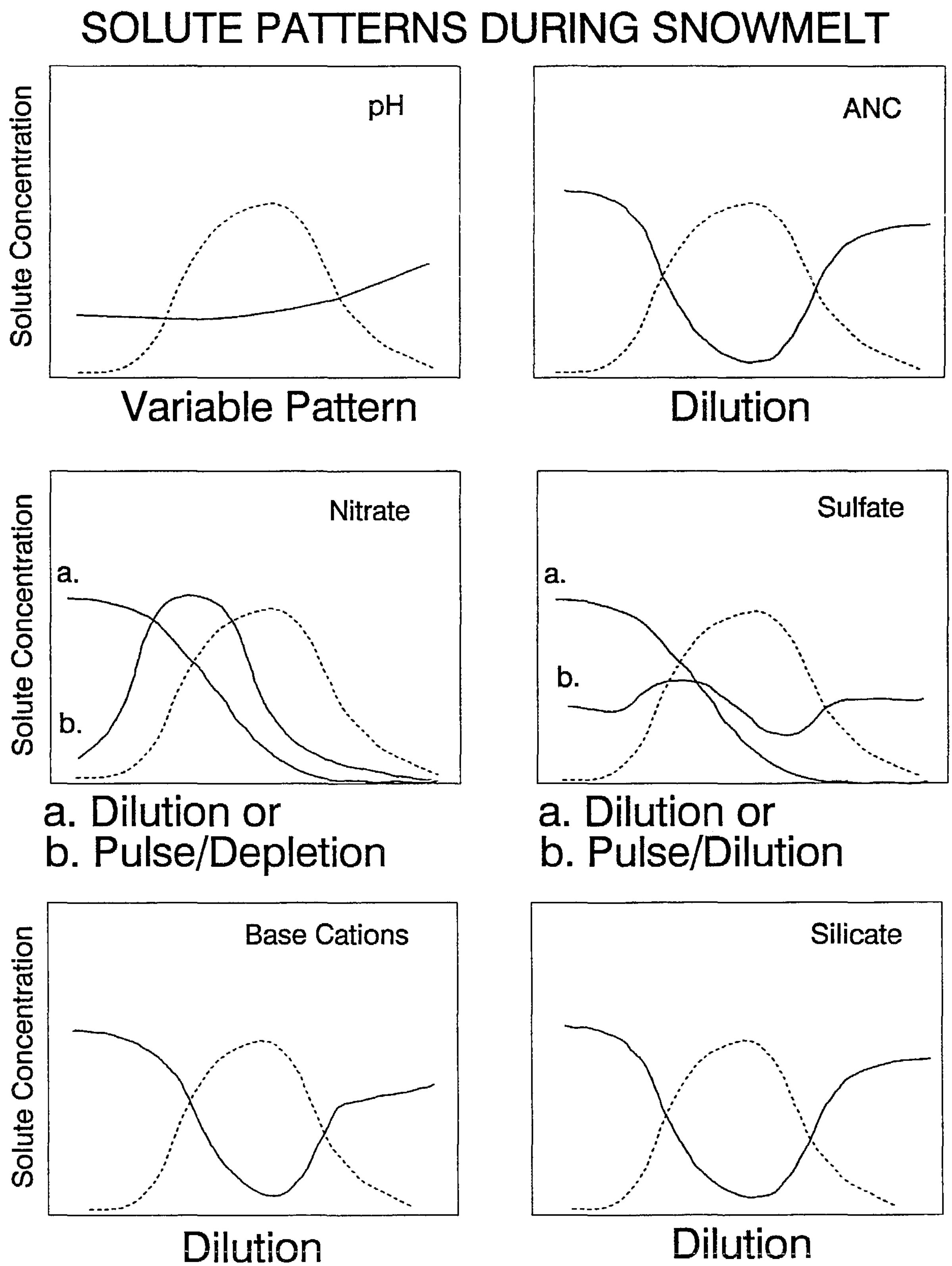
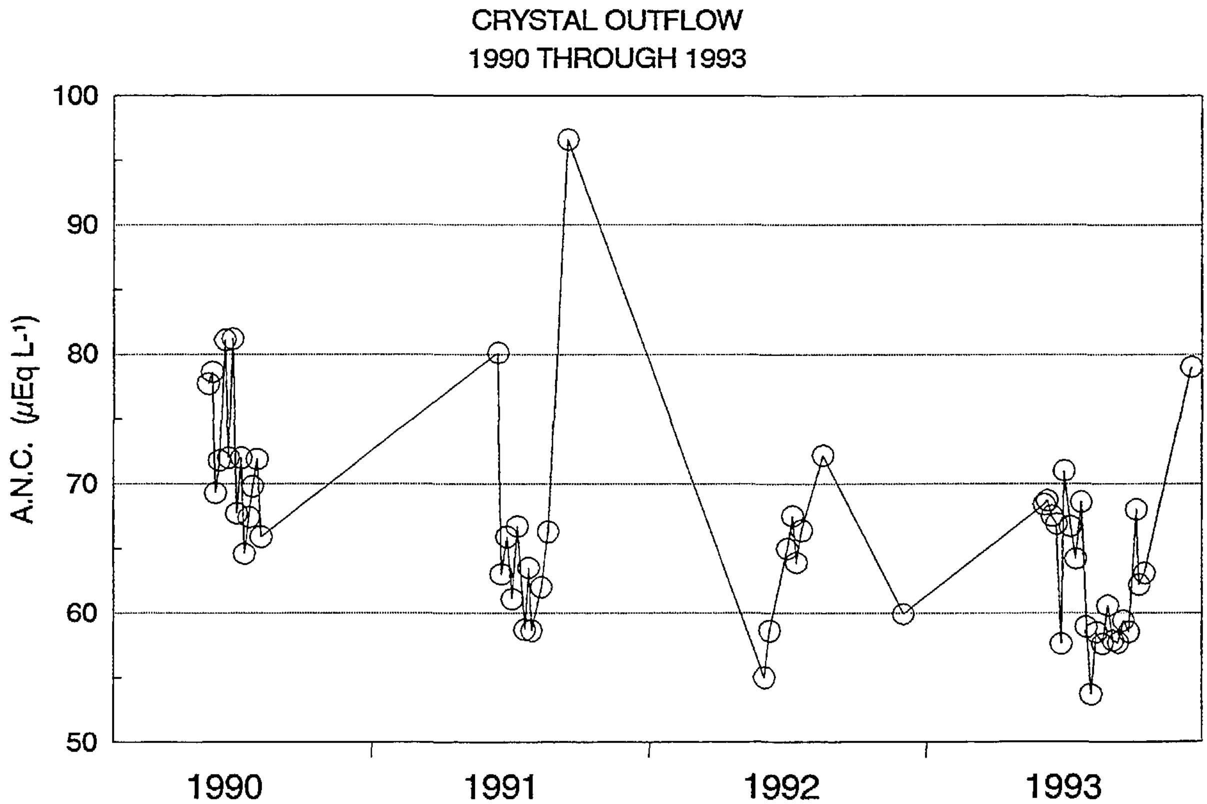


Figure I-85. Generalized patterns of solute concentration during snowmelt. Solid lines are concentration, dashed lines are discharge. Y axes show relative solute concentrations without scale. X-axes simulate the period of snowmelt.


CRYSTAL OUTFLOW
1990 THROUGH 1993
A.N.C. (μEq L^{-1})
100
90
80
70
60
50
1990
1991
1992
1993

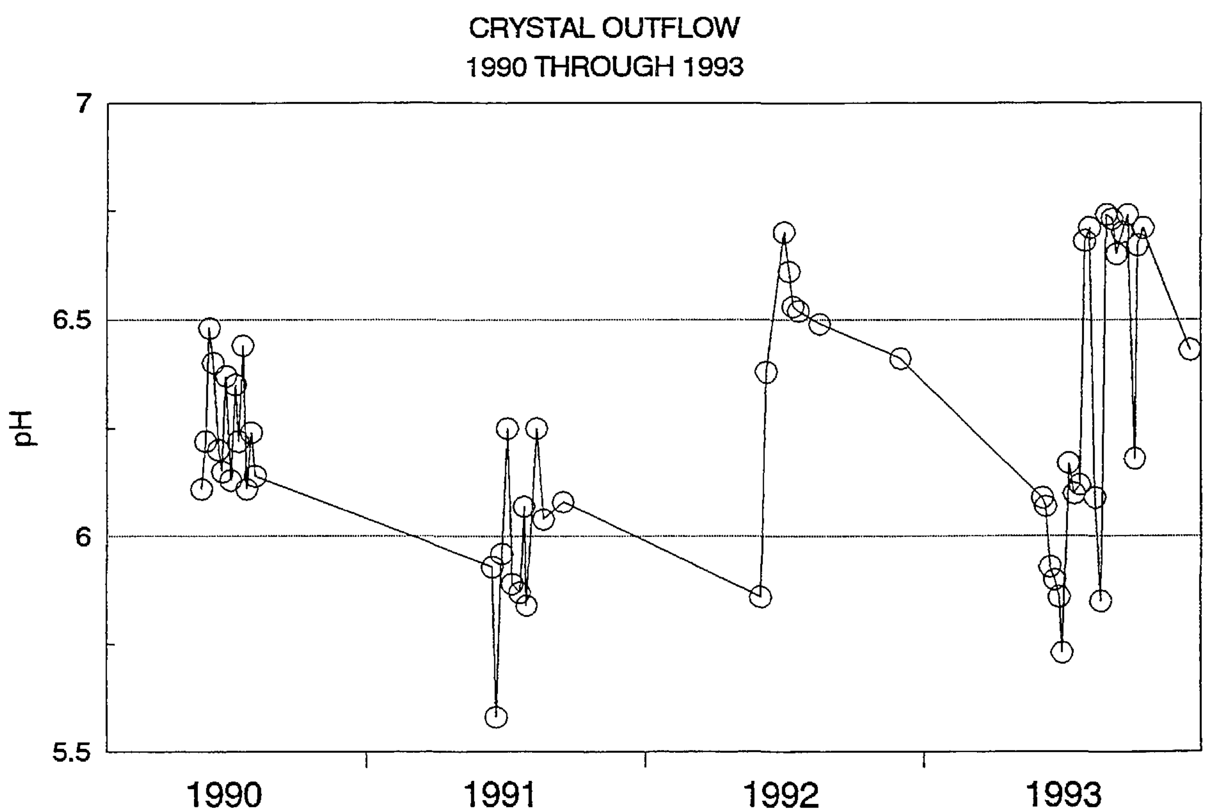
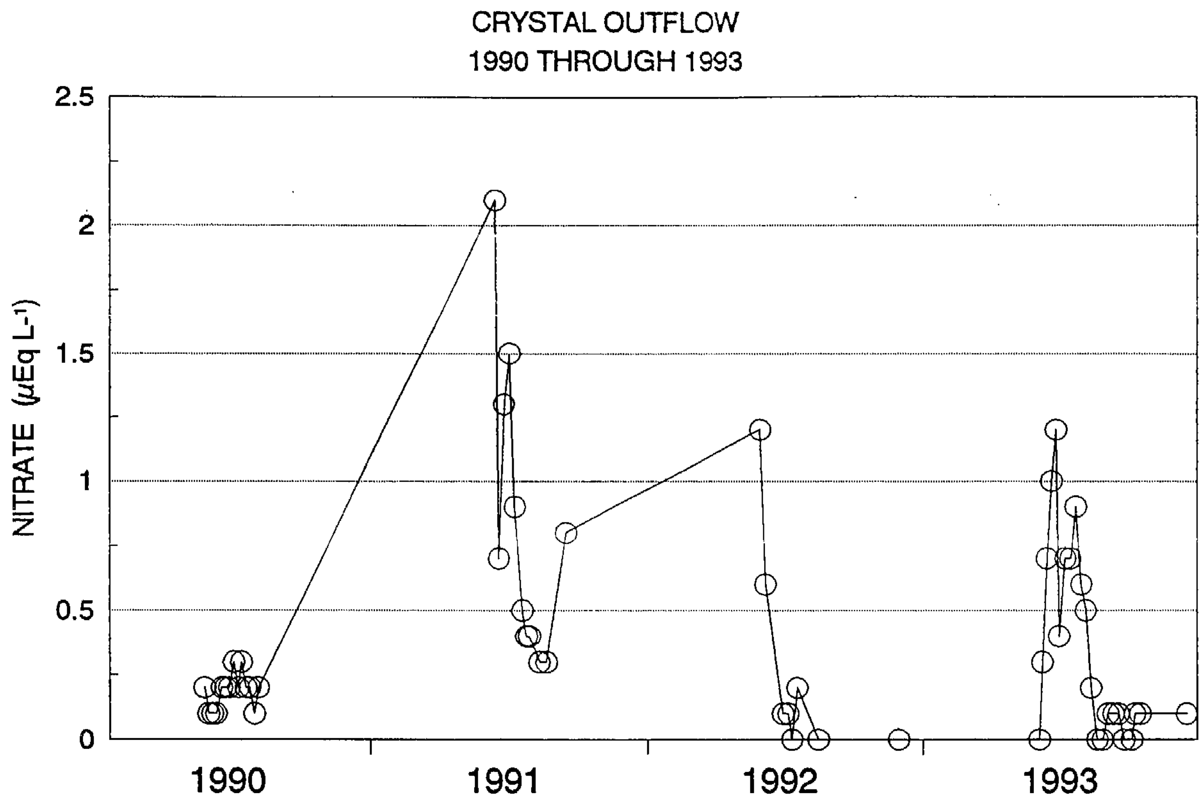

CRYSTAL OUTFLOW
1990 THROUGH 1993
pH
7
6.5
6
5.5
1990
1991
1992
1993

Figure I-86


CRYSTAL OUTFLOW
1990 THROUGH 1993
NITRATE (μEq L-1)
2.5
2
1.5
1
0.5
0
1990
1991
1992
1993

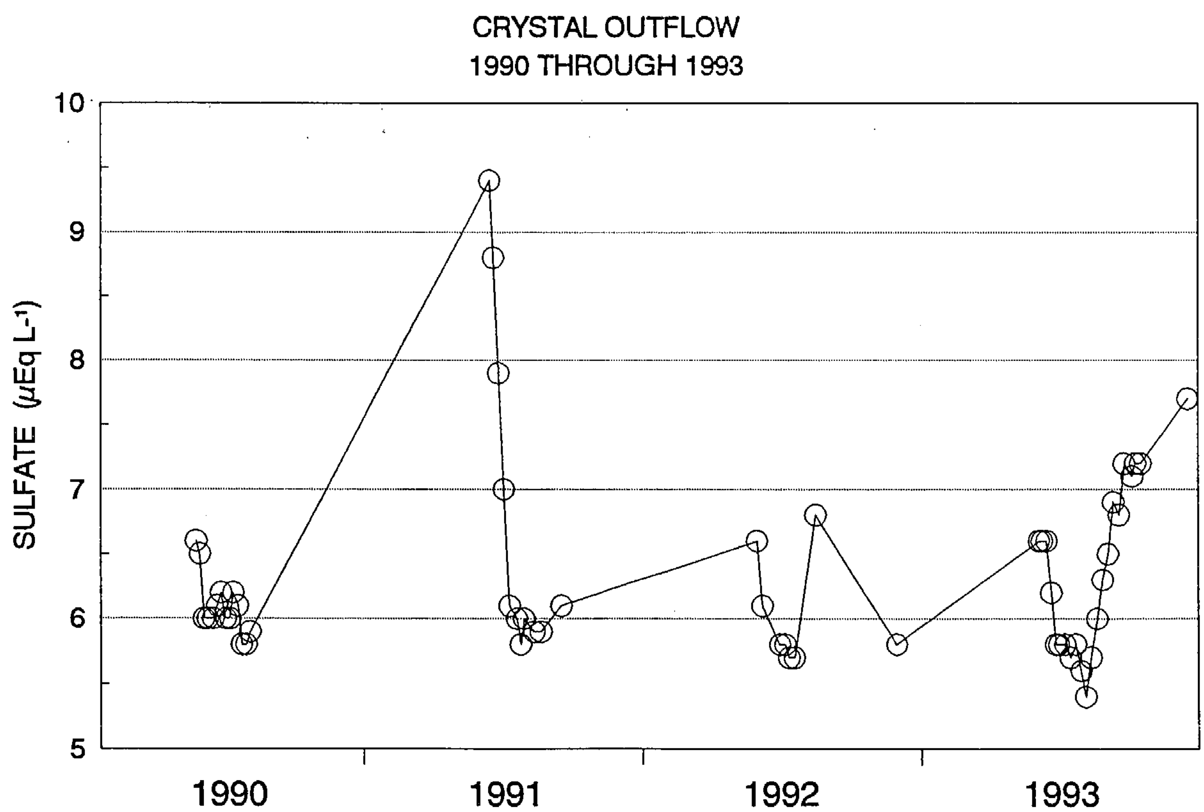
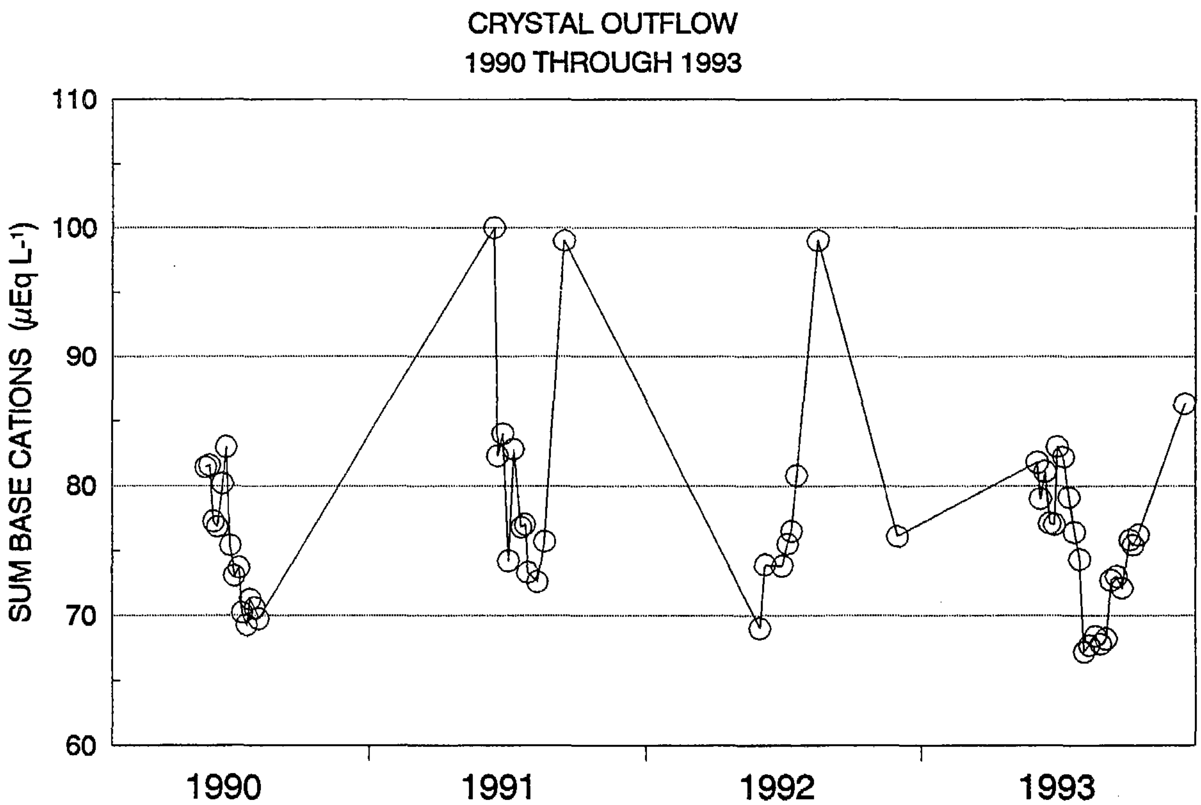

CRYSTAL OUTFLOW
1990 THROUGH 1993
SULFATE (μEq L-1)
10
9
8
7
6
5
1990
1991
1992
1993

Figure I-87


CRYSTAL OUTFLOW
1990 THROUGH 1993
SUM BASE CATIONS (µEq L-1)
110
100
90
80
70
60
1990
1991
1992
1993

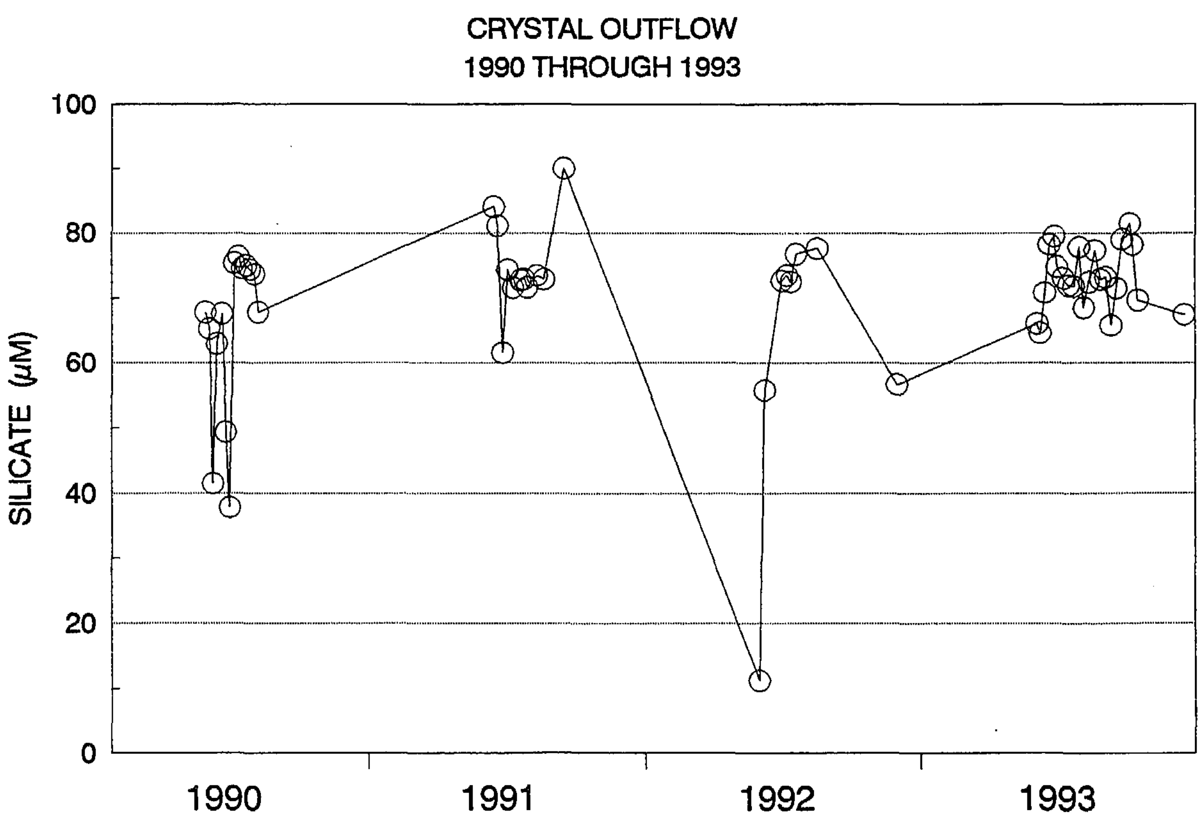
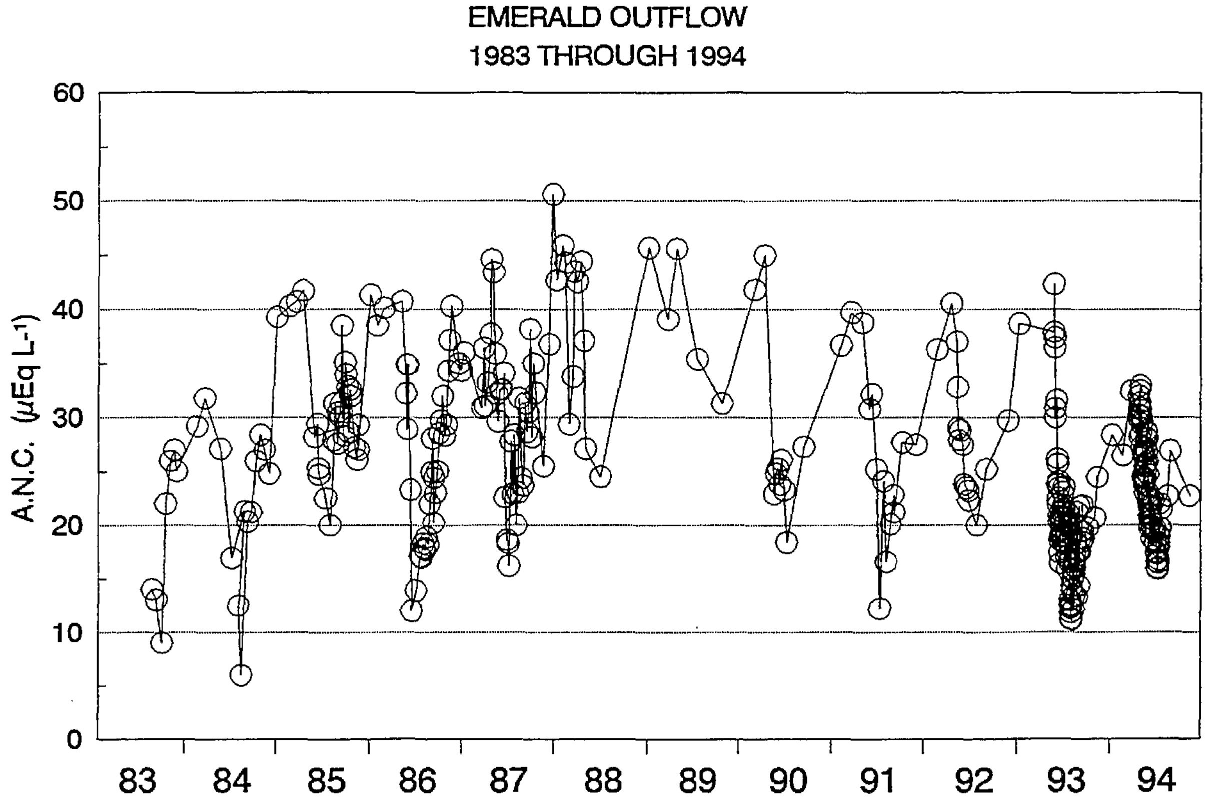
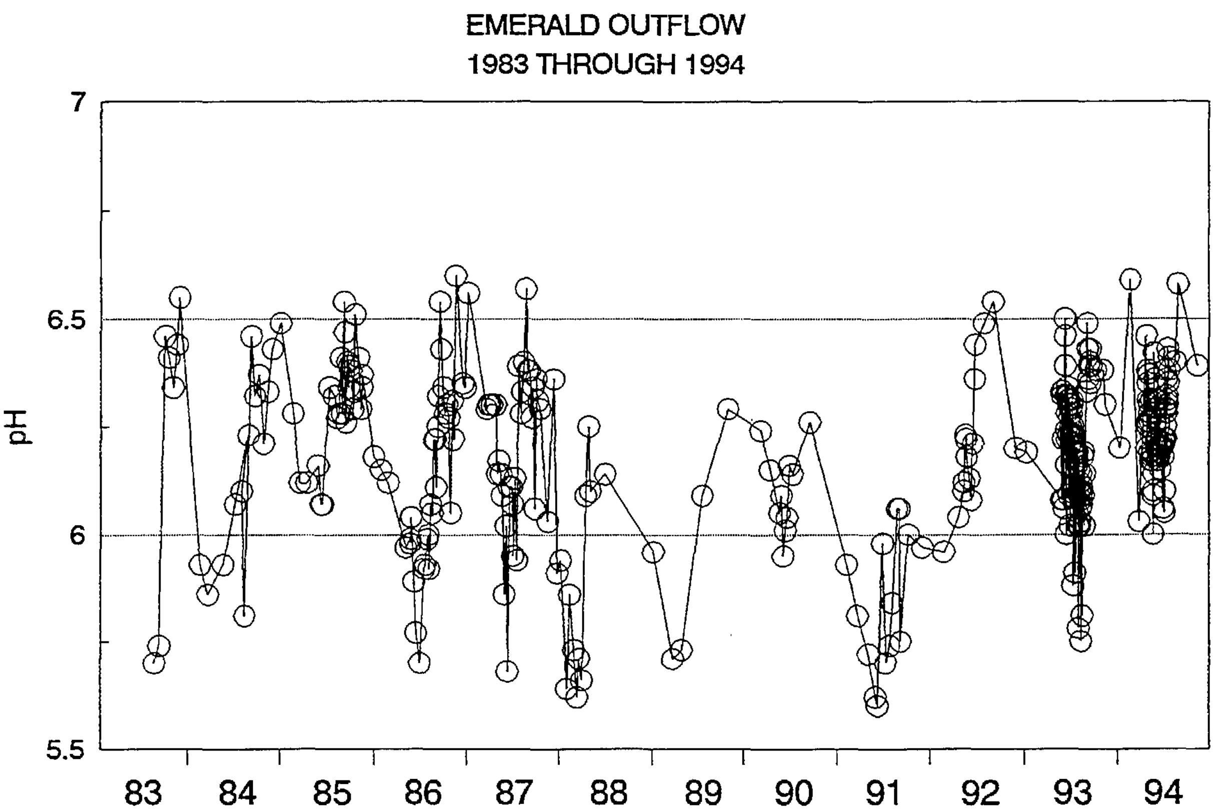

CRYSTAL OUTFLOW
1990 THROUGH 1993
SILICATE (µM)
100
80
60
40
20
0
1990
1991
1992
1993

Figure I-88

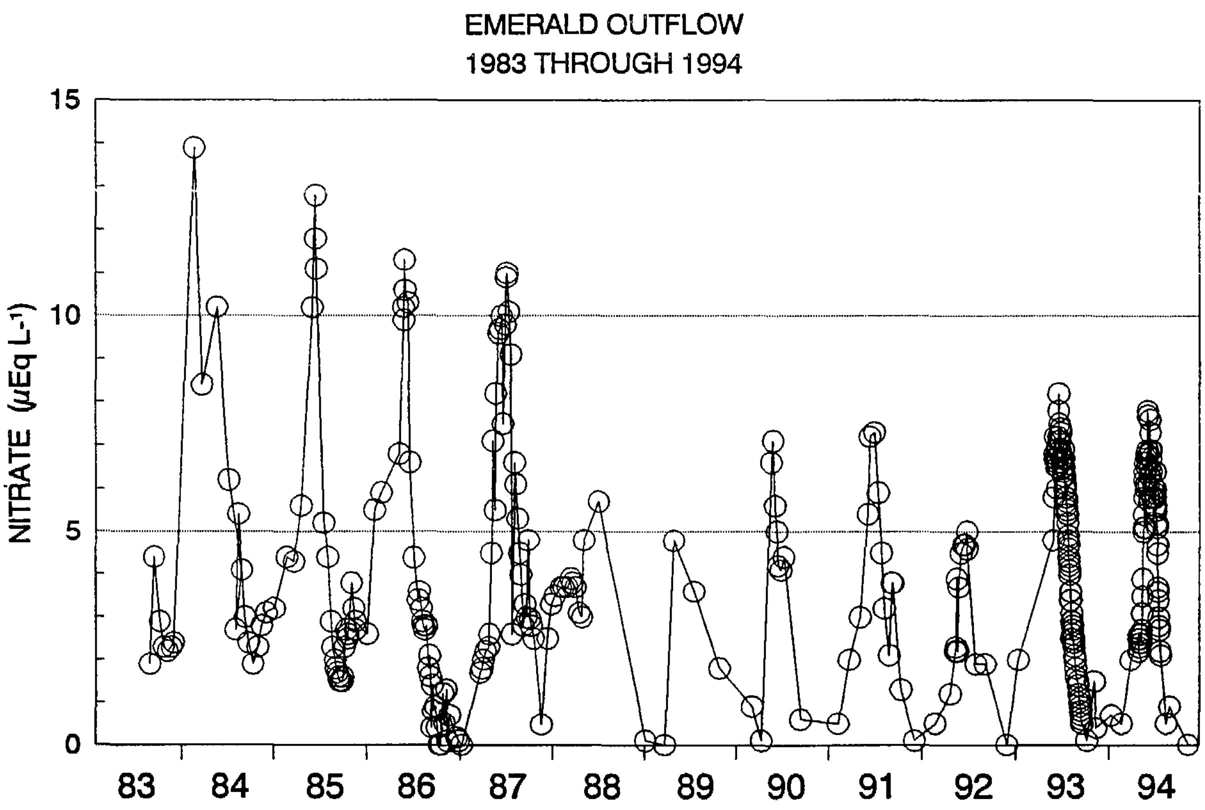


EMERALD OUTFLOW
1983 THROUGH 1994
A.N.C. (µEq L-1)
60
50
40
30
20
10
0
83
84
85
86
87
88
89
90
91
92
93
94



EMERALD OUTFLOW
1983 THROUGH 1994
pH
7
6.5
6
5.5
83
84
85
86
87
88
89
90
91
92
93
94

Figure I-89


EMERALD OUTFLOW
1983 THROUGH 1994
NITRATE (μEq L-1)
15
10
5
0
83
84
85
86
87
88
89
90
91
92
93
94

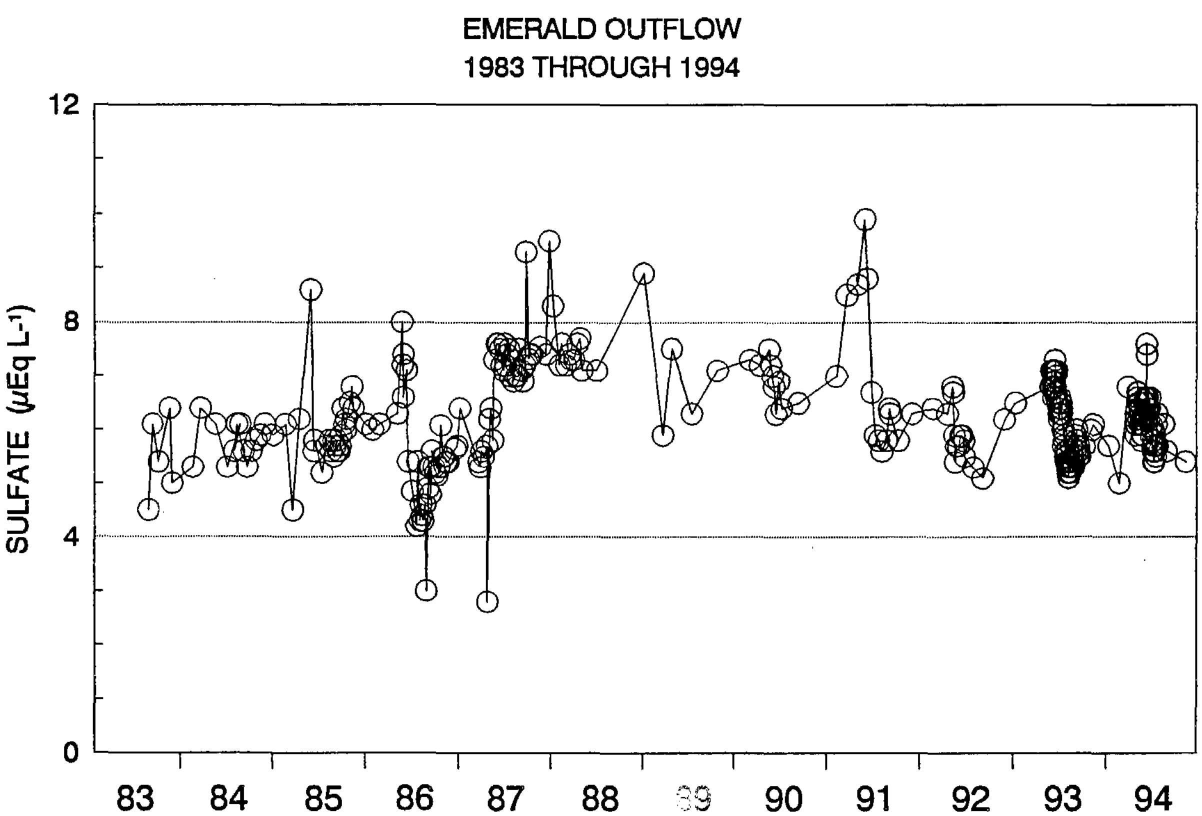
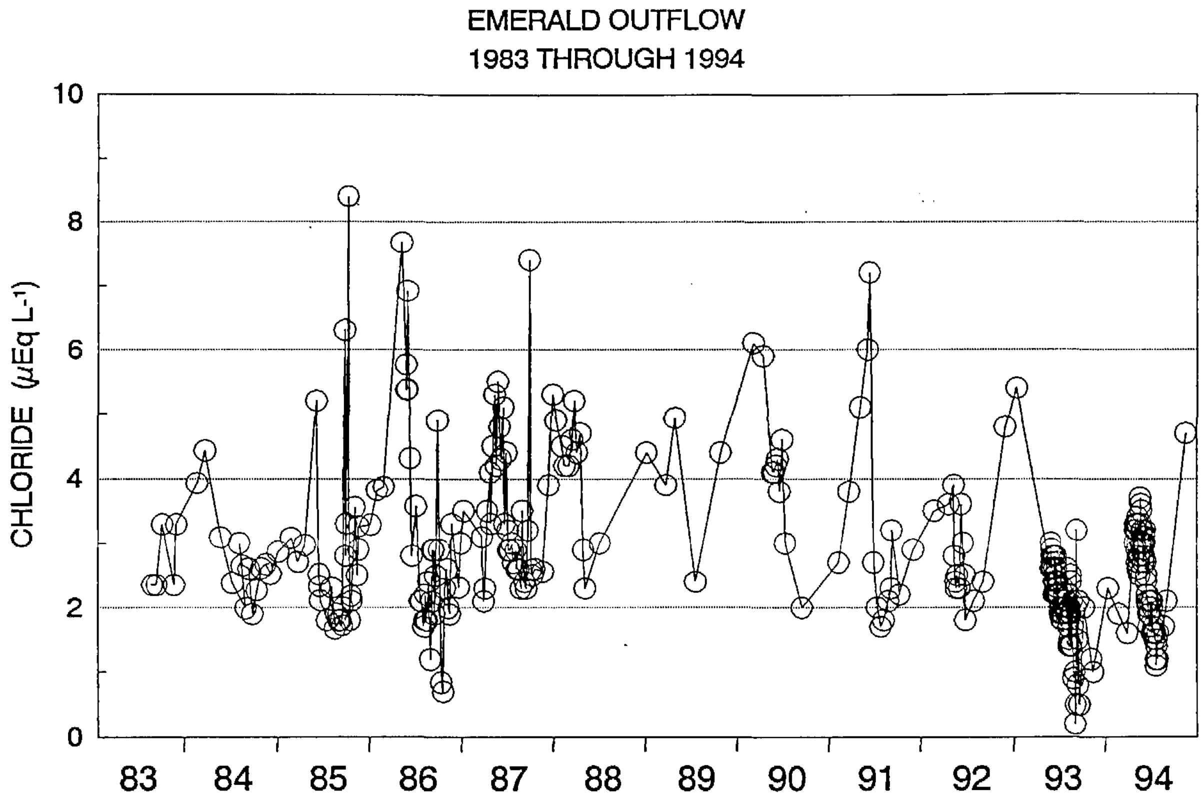

EMERALD OUTFLOW
1983 THROUGH 1994
SULFATE (μEq L-1)
12
8
4
0
83
84
85
86
87
88
89
90
91
92
93
94

Figure I-90


EMERALD OUTFLOW
1983 THROUGH 1994
CHLORIDE (μEq L^{-1})
10
8
6
4
2
0
83
84
85
86
87
88
89
90
91
92
93
94

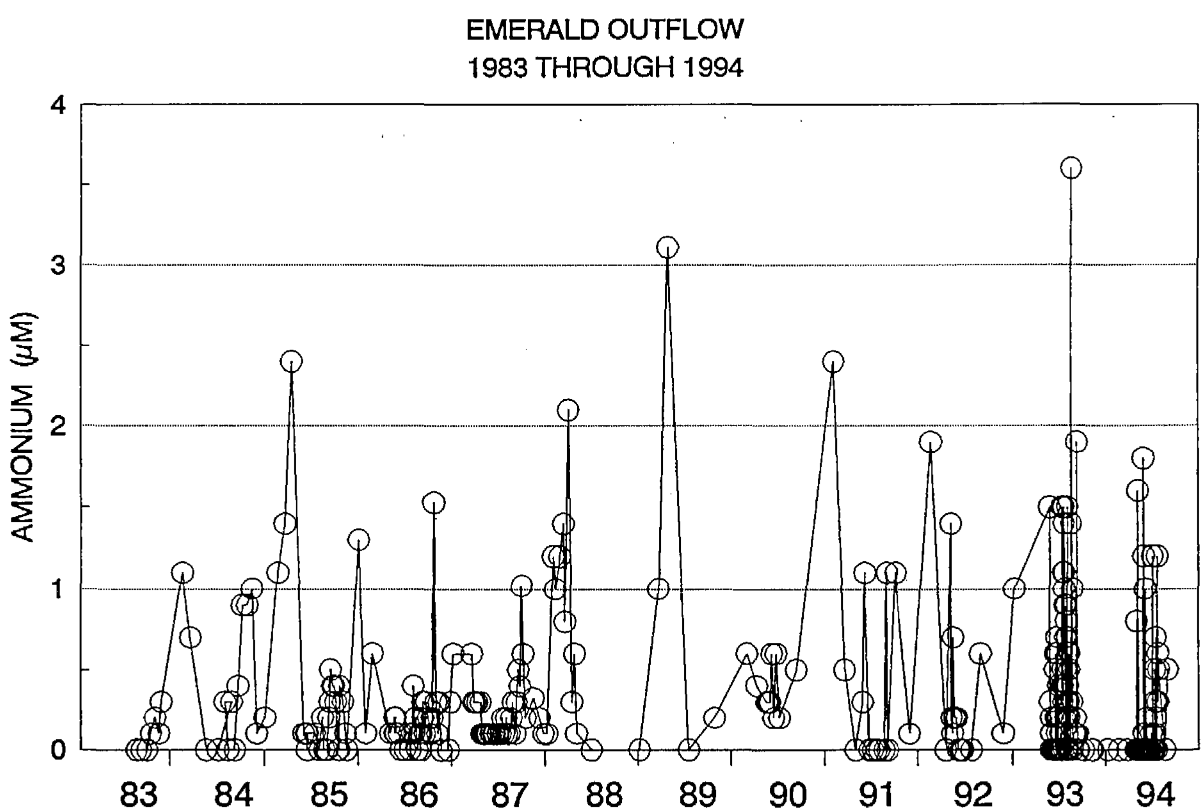
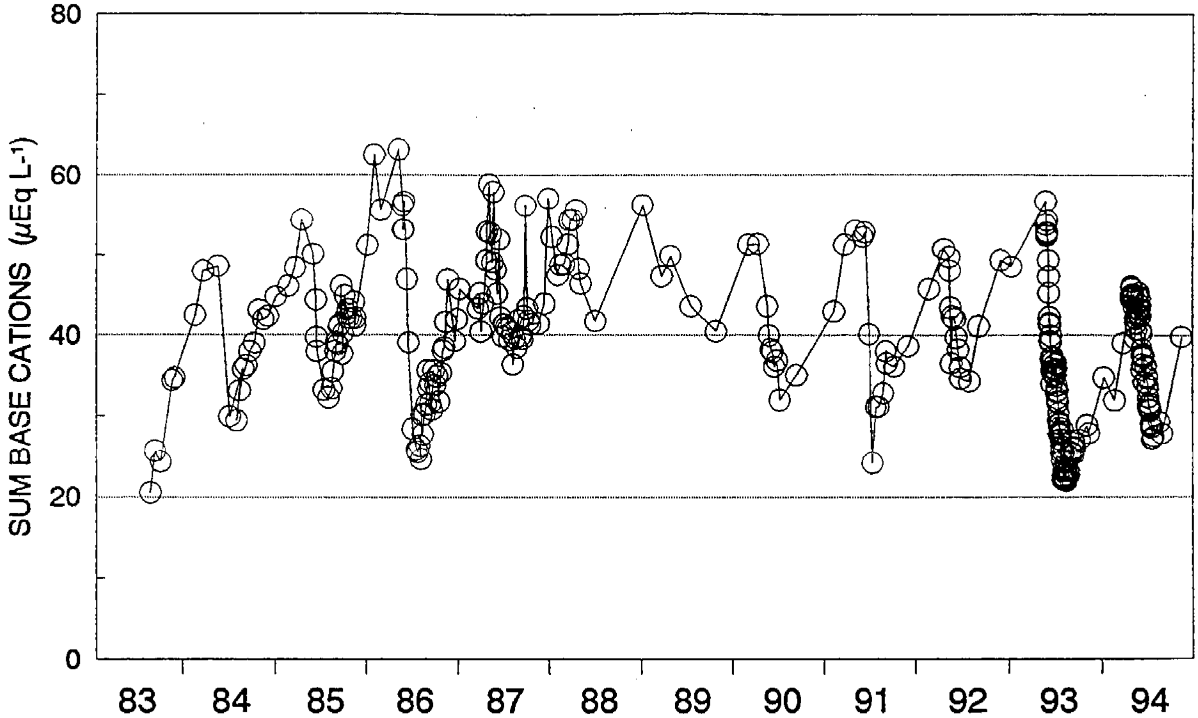

EMERALD OUTFLOW
1983 THROUGH 1994
AMMONIUM (μM)
4
3
2
1
0
83
84
85
86
87
88
89
90
91
92
93
94

Figure I-91

EMERALD OUTFLOW
1983 THROUGH 1994



EMERALD OUTFLOW
1983 THROUGH 1994

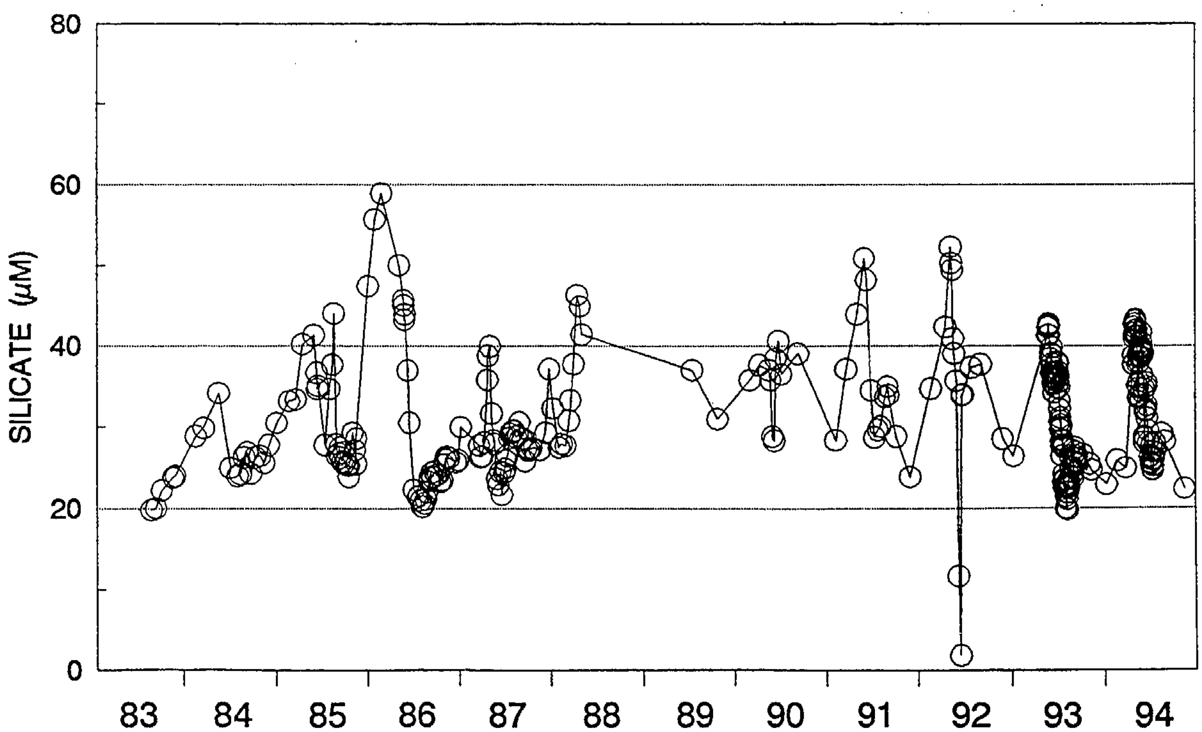
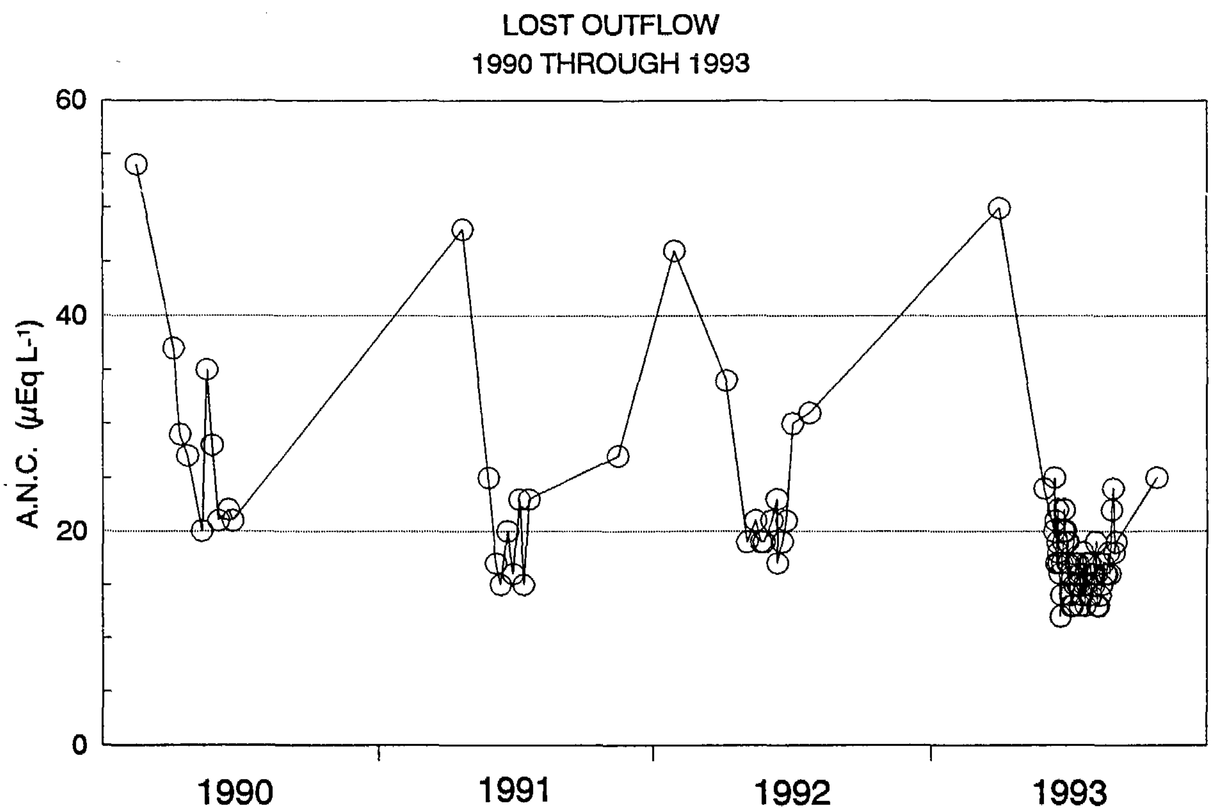


Figure I-92


LOST OUTFLOW
1990 THROUGH 1993
A.N.C. (μEq L-1)
60
40
20
0
1990
1991
1992
1993

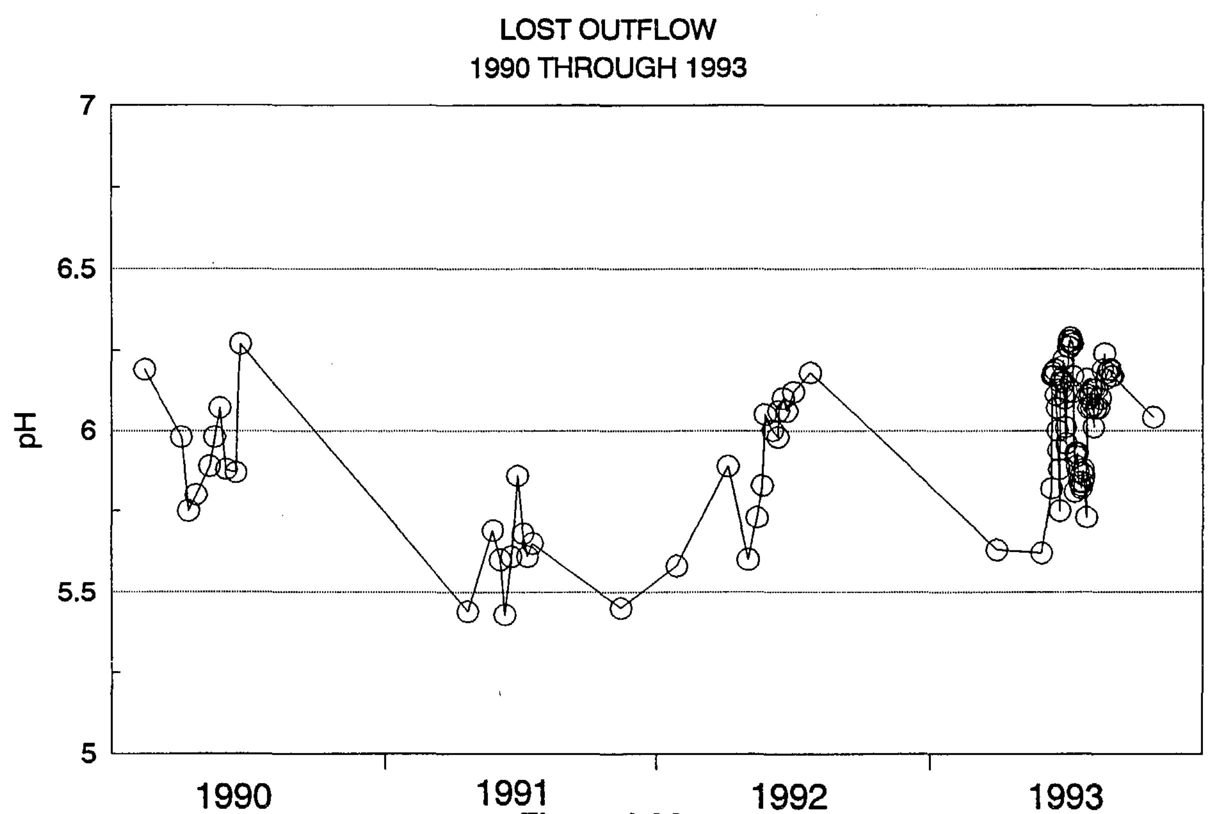
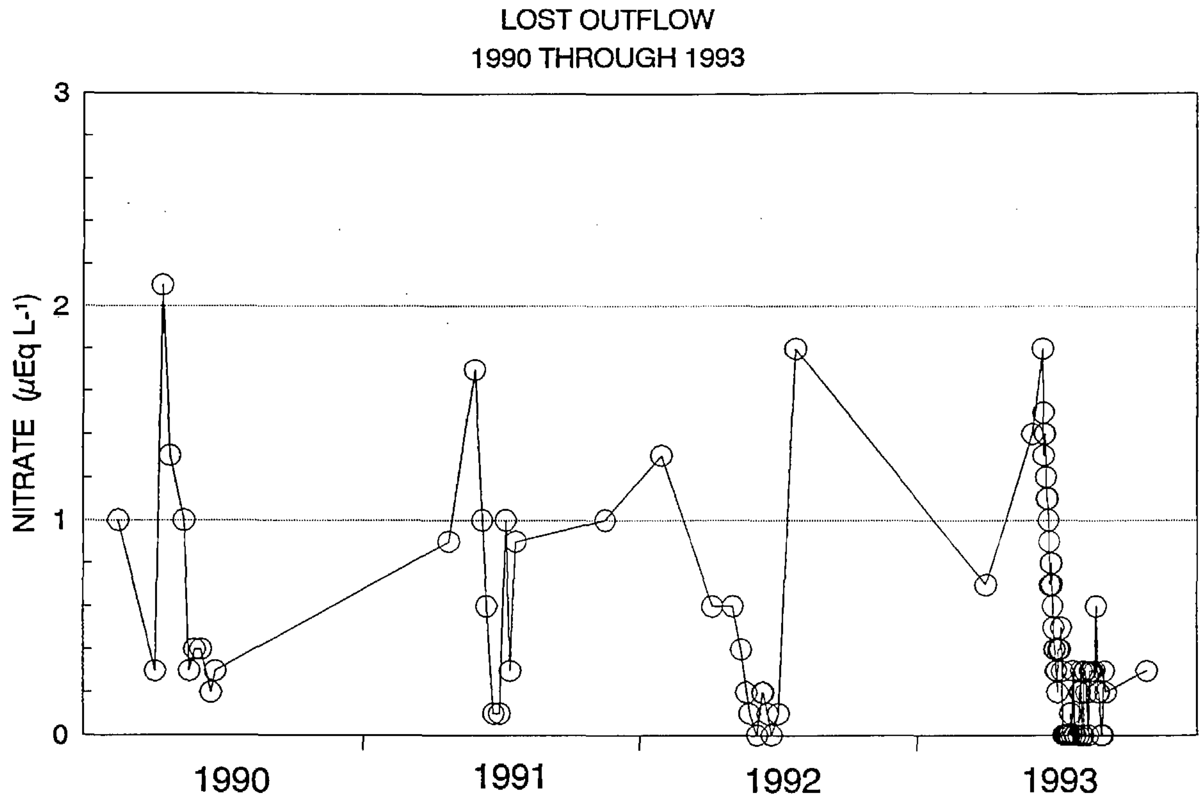

LOST OUTFLOW
1990 THROUGH 1993
pH
7
6.5
6
5.5
5
1990
1991
1992
1993

Figure I-93


LOST OUTFLOW
1990 THROUGH 1993
NITRATE (μEq L^{-1})
0
1
2
3
1990
1991
1992
1993

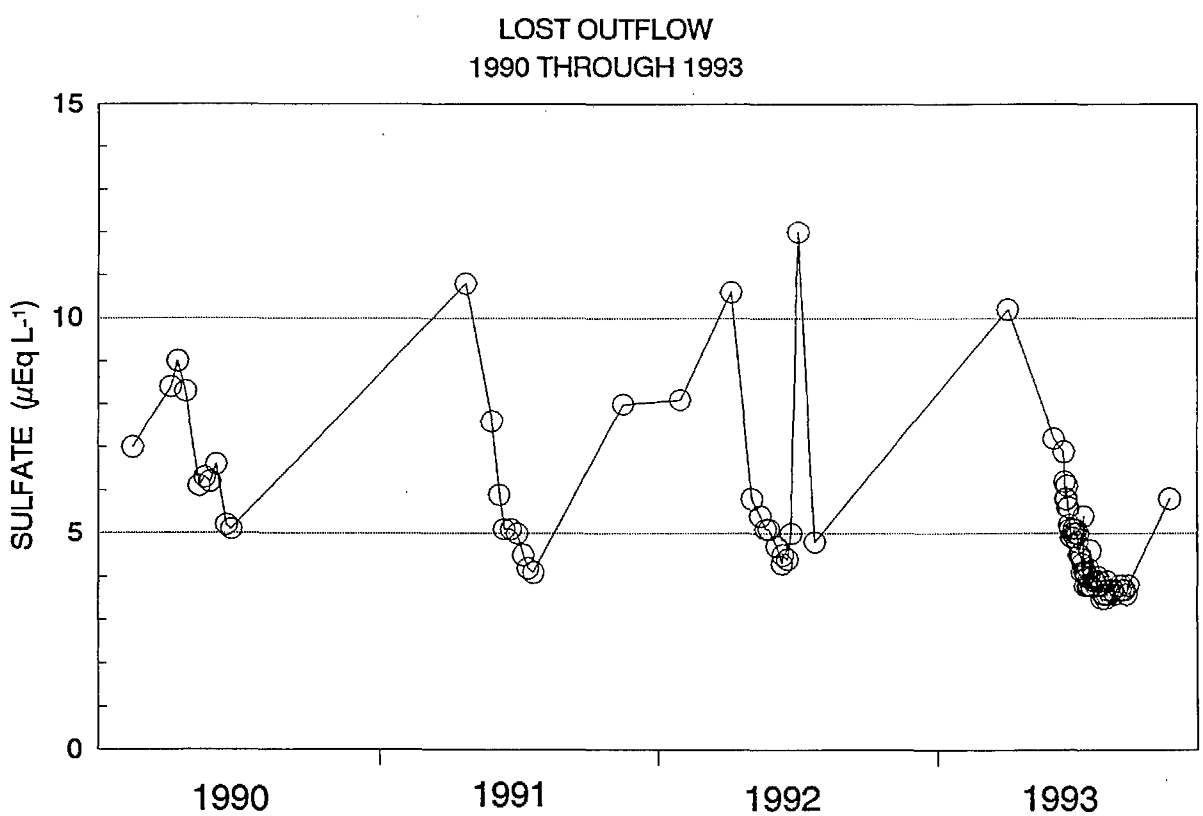
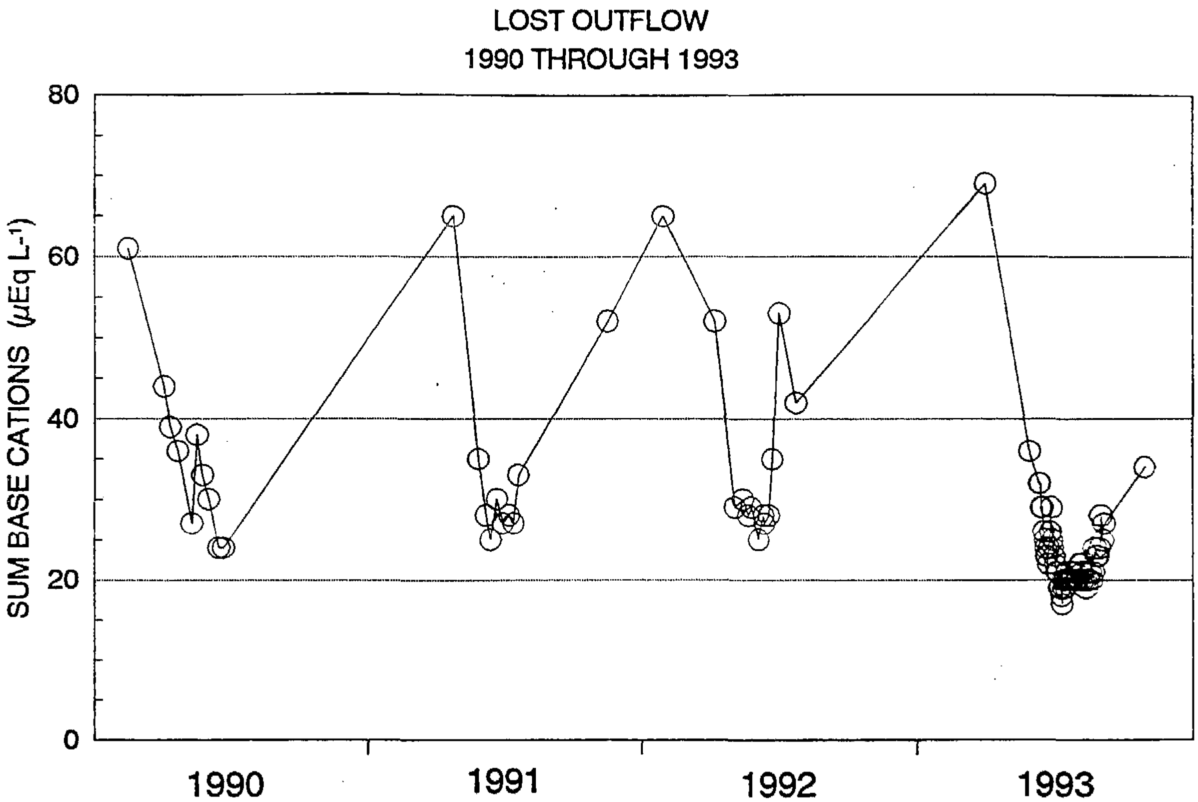

LOST OUTFLOW
1990 THROUGH 1993
SULFATE (μEq L^{-1})
0
5
10
15
1990
1991
1992
1993

Figure I-94


LOST OUTFLOW
1990 THROUGH 1993
SUM BASE CATIONS (μEq L^{-1})
80
60
40
20
0
1990
1991
1992
1993

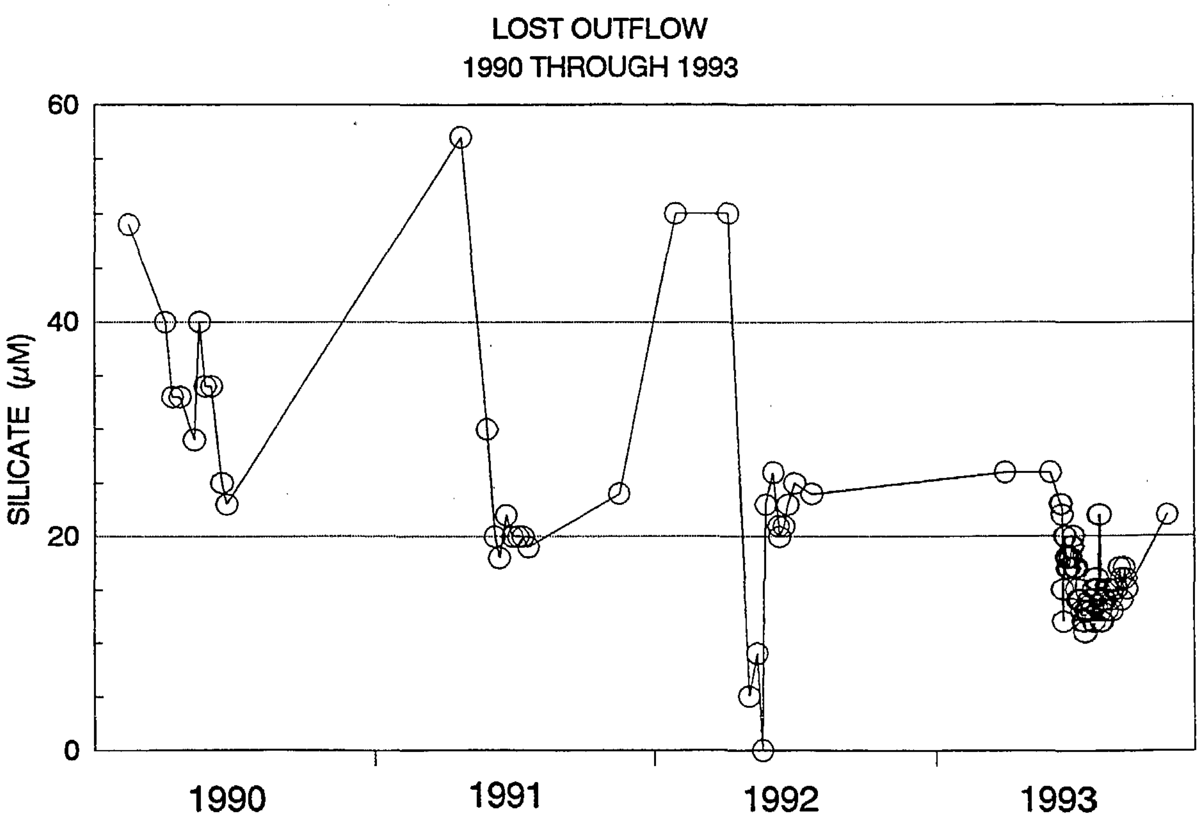
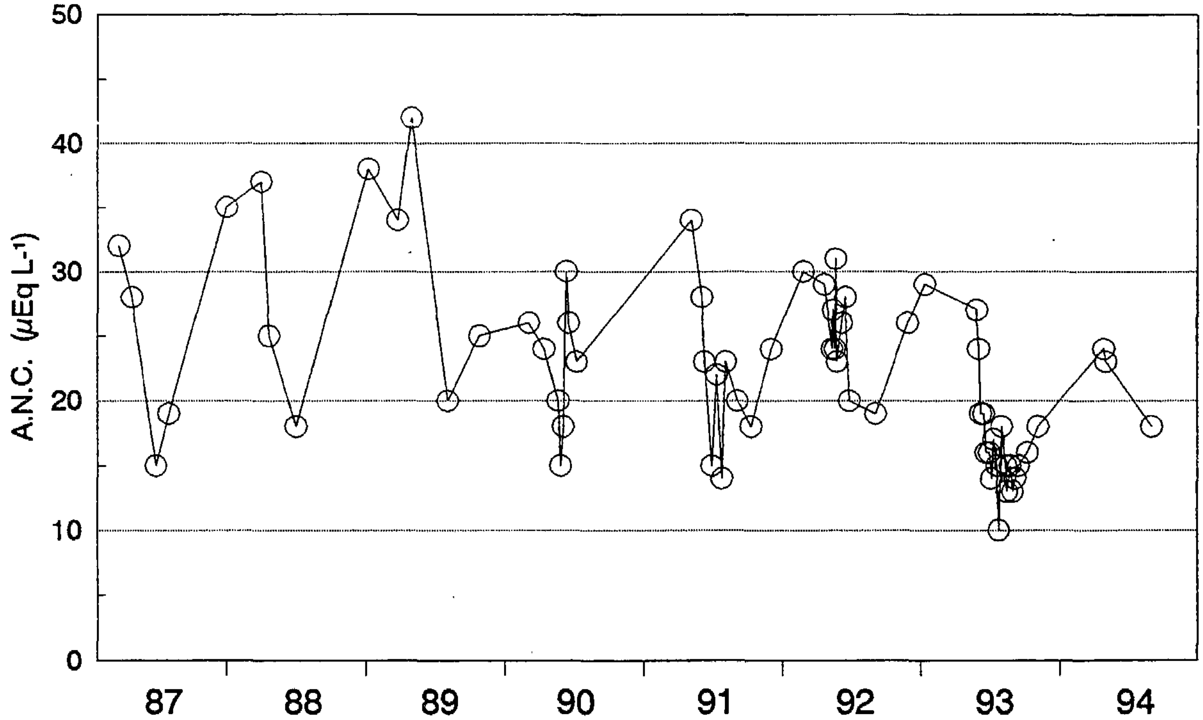

LOST OUTFLOW
1990 THROUGH 1993
SILICATE (μM)
60
40
20
0
1990
1991
1992
1993

Figure I-95

PEAR OUTFLOW
1987 THROUGH 1994



PEAR OUTFLOW
1987 THROUGH 1994

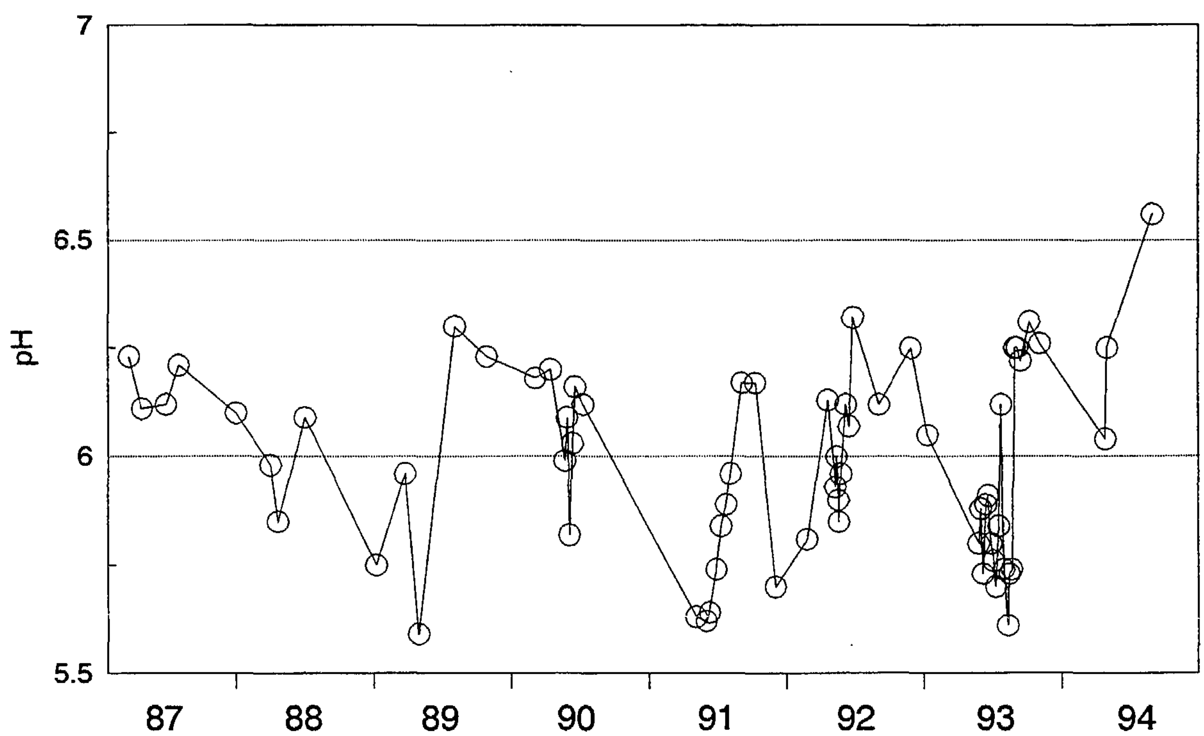
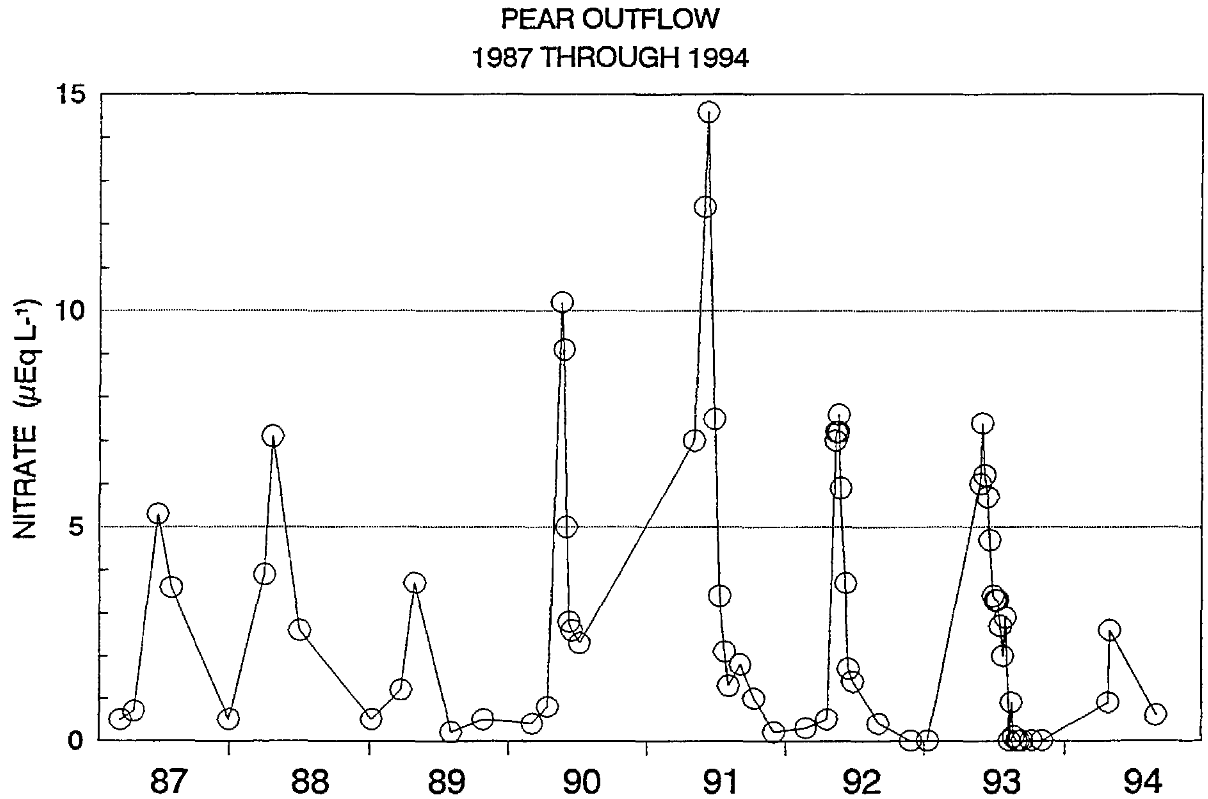


Figure I-96


PEAR OUTFLOW
1987 THROUGH 1994
NITRATE (μEq L-1)
15
10
5
0
87
88
89
90
91
92
93
94

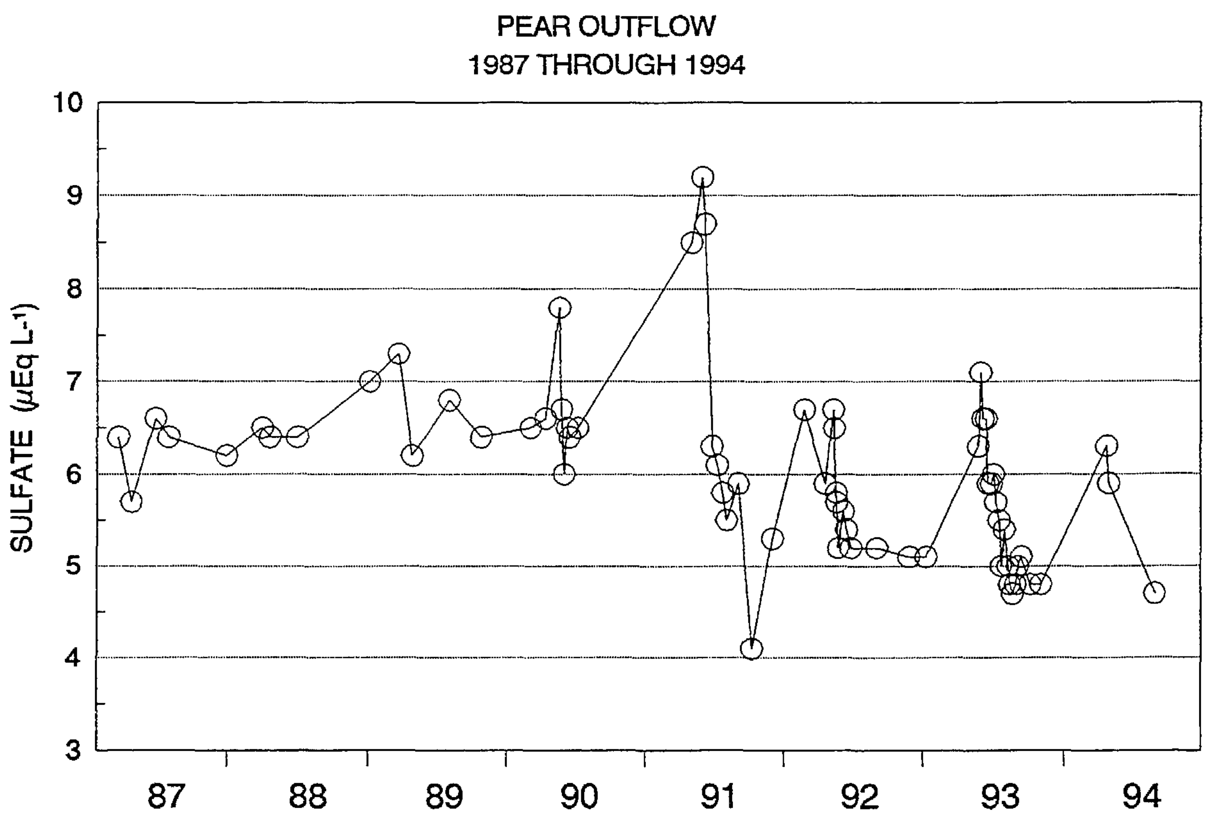
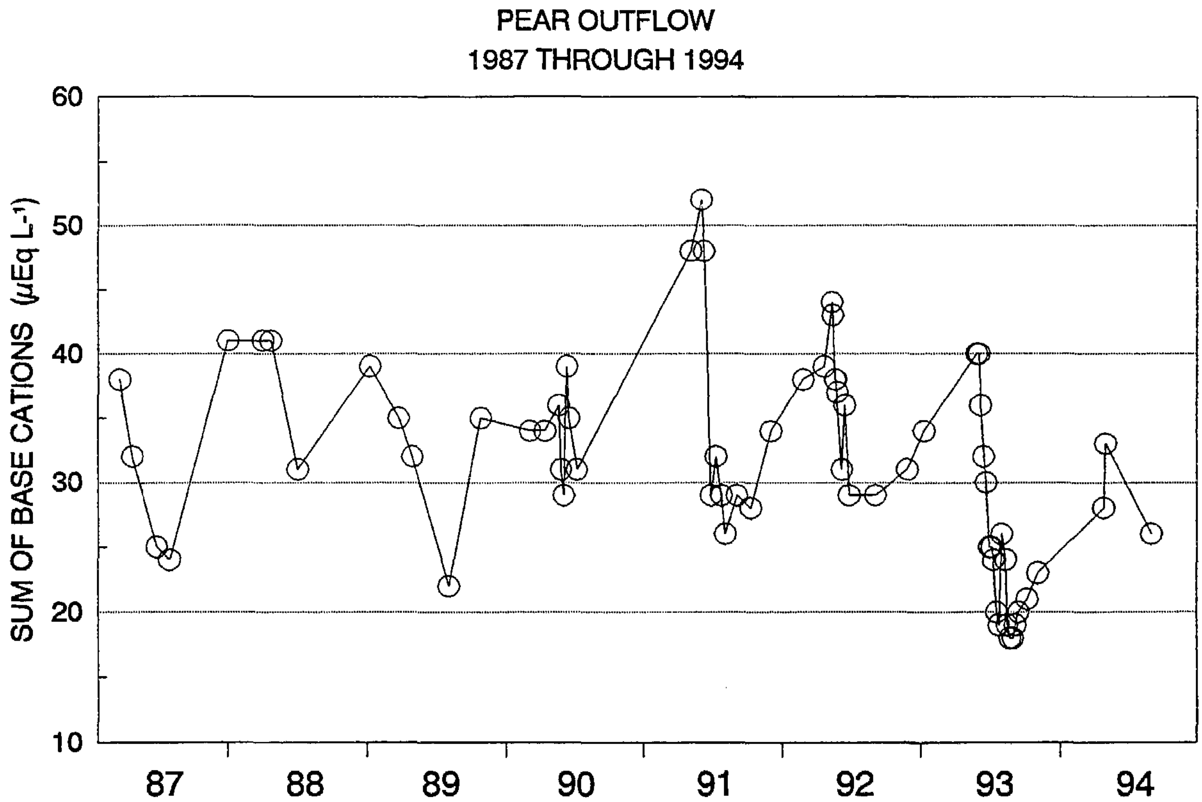

PEAR OUTFLOW
1987 THROUGH 1994
SULFATE (μEq L-1)
10
9
8
7
6
5
4
3
87
88
89
90
91
92
93
94

Figure I-97


PEAR OUTFLOW
1987 THROUGH 1994
SUM OF BASE CATIONS (μEq L-1)
60
50
40
30
20
10
87
88
89
90
91
92
93
94

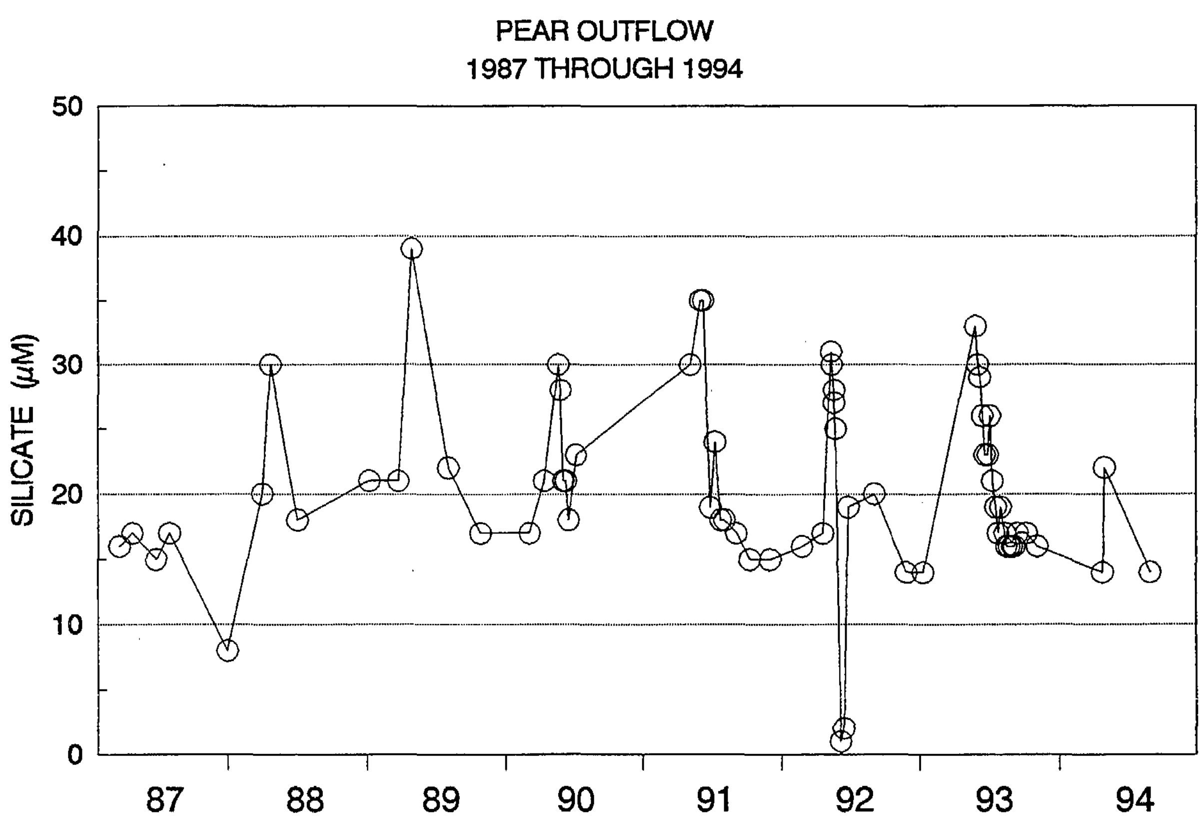

PEAR OUTFLOW
1987 THROUGH 1994
SILICATE (μM)
50
40
30
20
10
0
87
88
89
90
91
92
93
94

Figure I-98

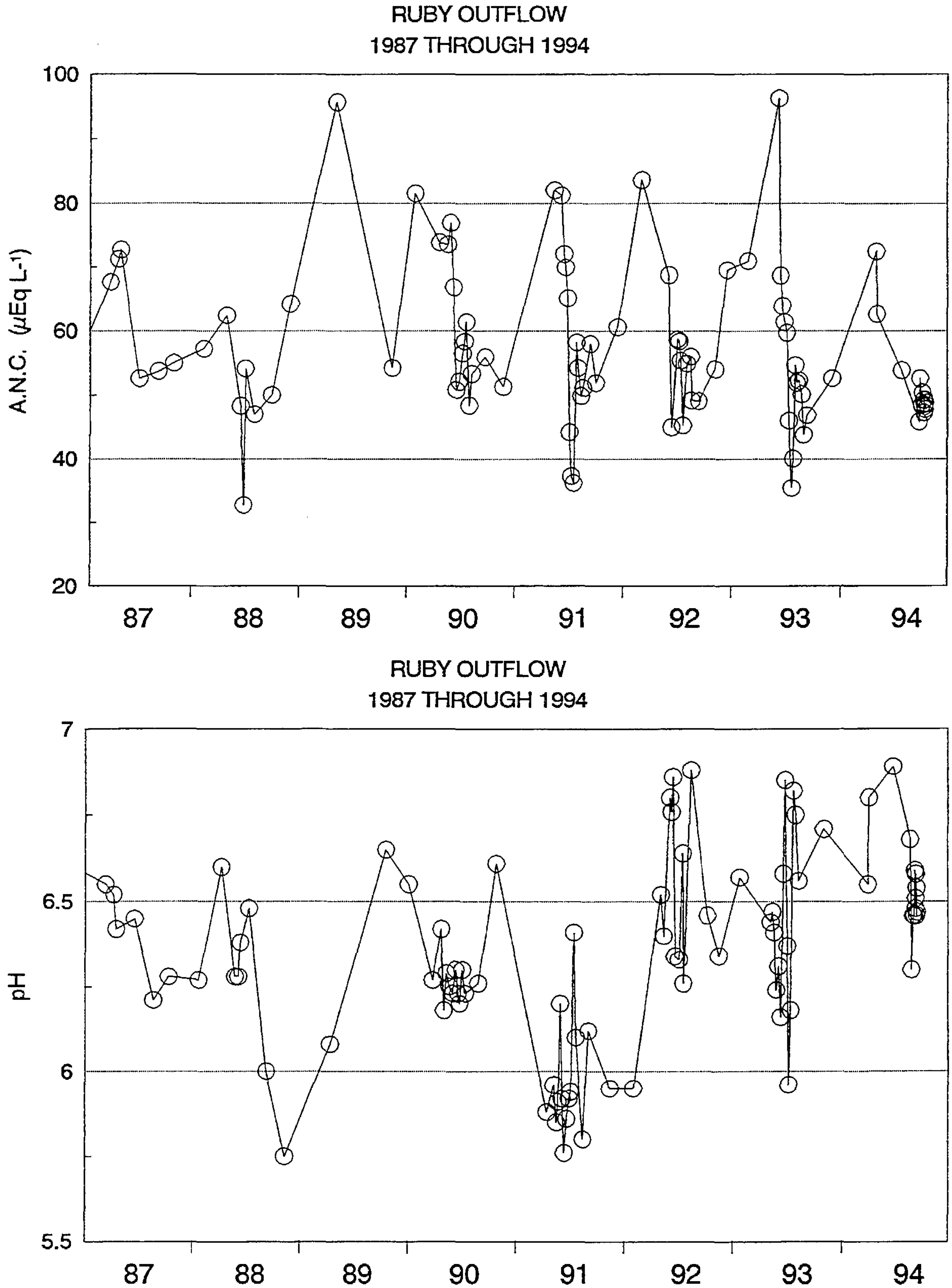
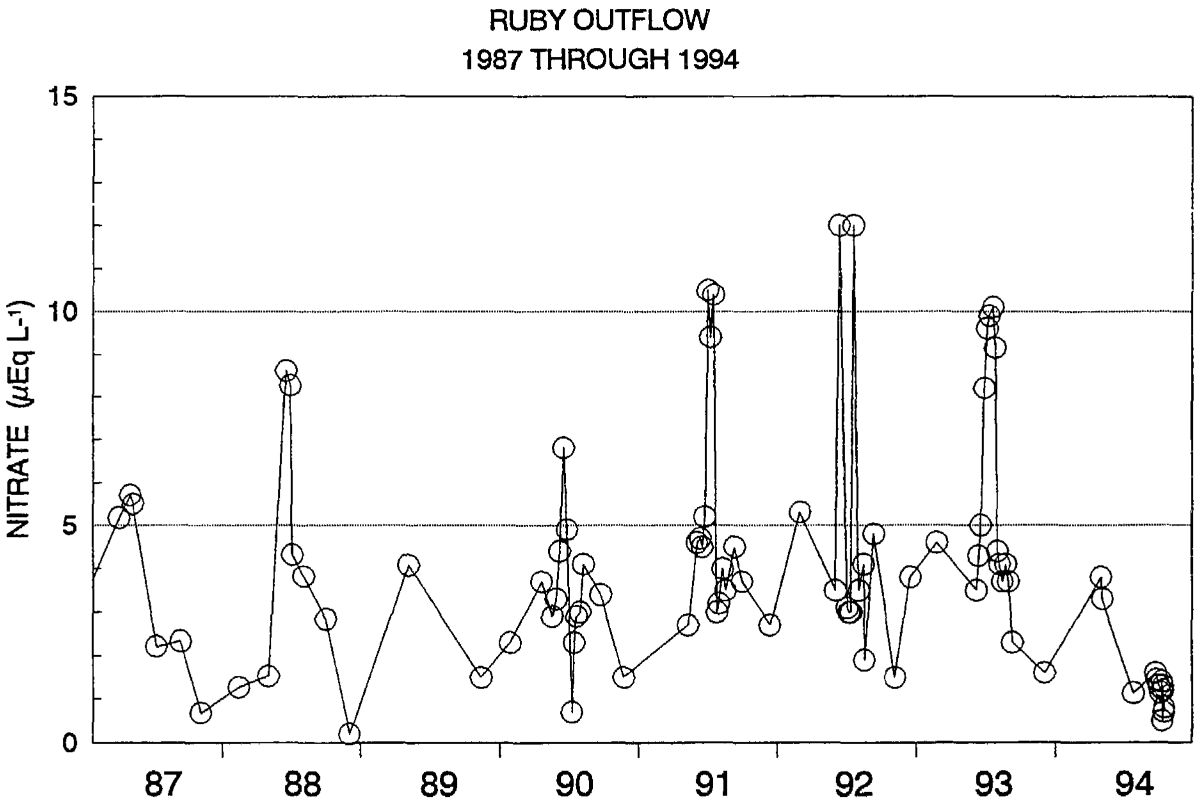

RUBY OUTFLOW
1987 THROUGH 1994
A.N.C. (μEq L-1)
100
80
60
40
20
87
88
89
90
91
92
93
94
RUBY OUTFLOW
1987 THROUGH 1994
pH
7
6.5
6
5.5
87
88
89
90
91
92
93
94

Figure I-99


RUBY OUTFLOW
1987 THROUGH 1994
NITRATE (μEq L⁻¹)
15
10
5
0
87
88
89
90
91
92
93
94

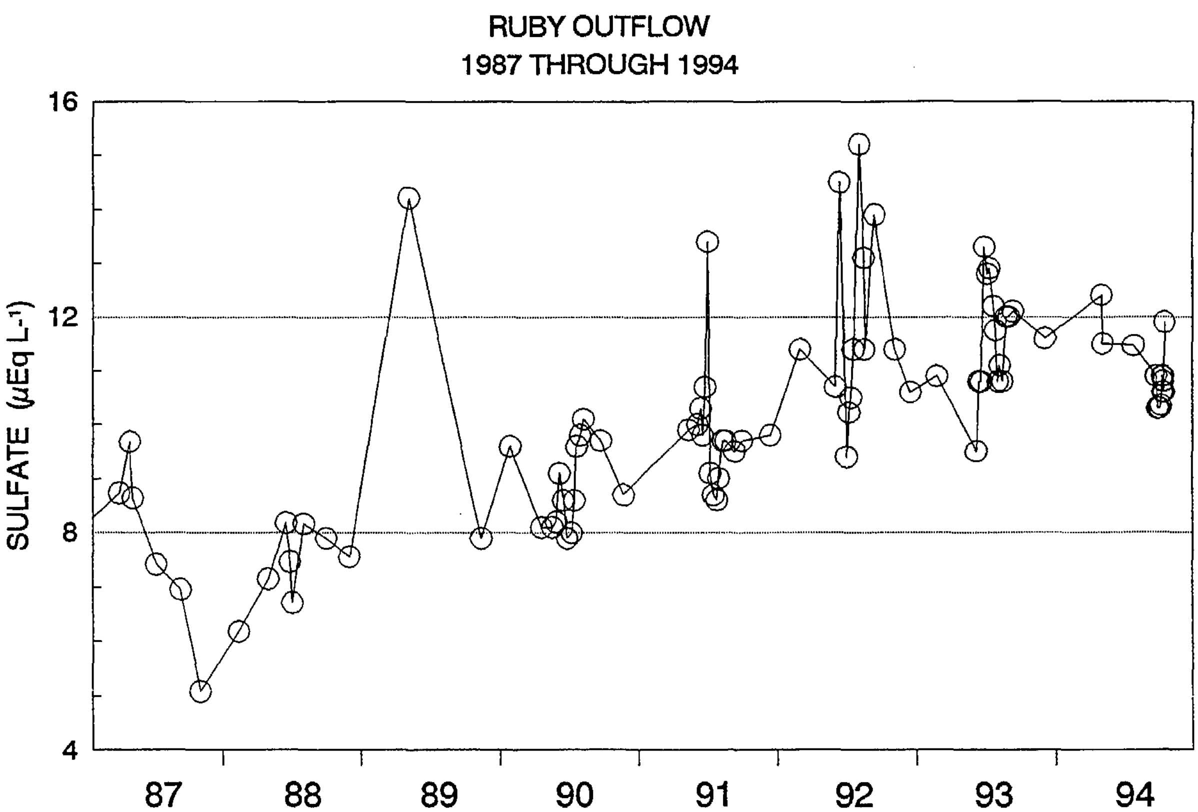
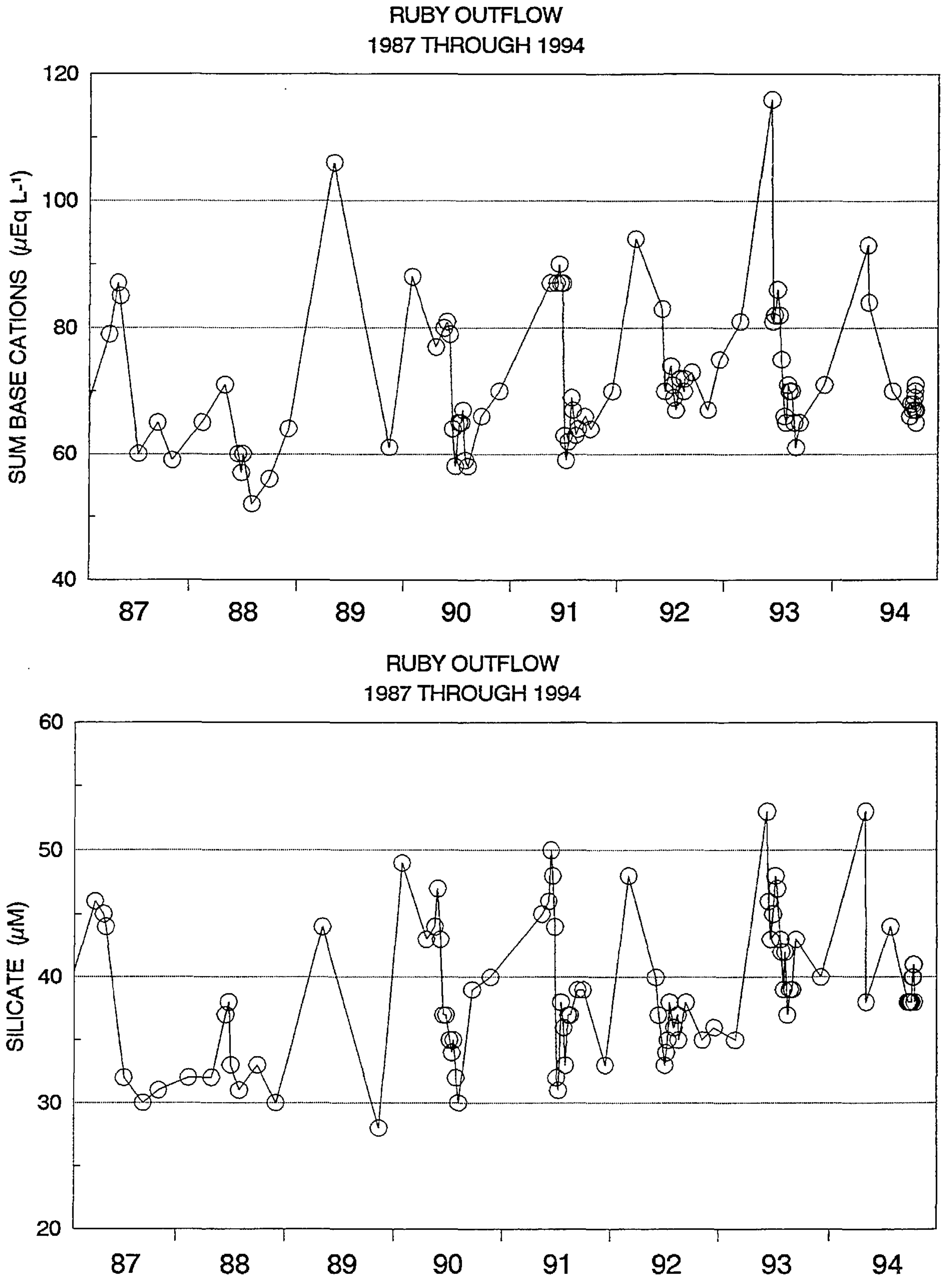

RUBY OUTFLOW
1987 THROUGH 1994
SULFATE (μEq L⁻¹)
16
12
8
4
87
88
89
90
91
92
93
94

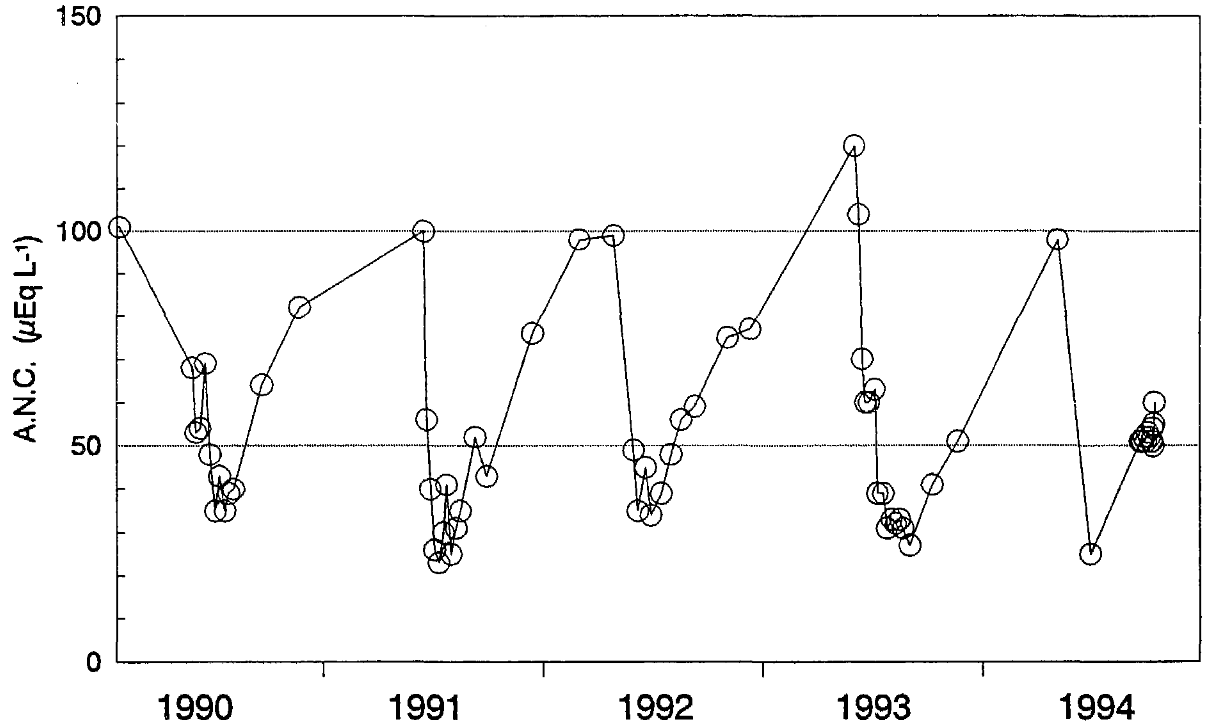
Figure I-100



RUBY OUTFLOW
1987 THROUGH 1994
SUM BASE CATIONS (μEq L-1)
120
100
80
60
40
87
88
89
90
91
92
93
94
RUBY OUTFLOW
1987 THROUGH 1994
SILICATE (μM)
60
50
40
30
20
87
88
89
90
91
92
93
94

Figure I-101

SPULLER OUTFLOW
1990 THROUGH 1994



SPULLER OUTFLOW
1990 THROUGH 1994

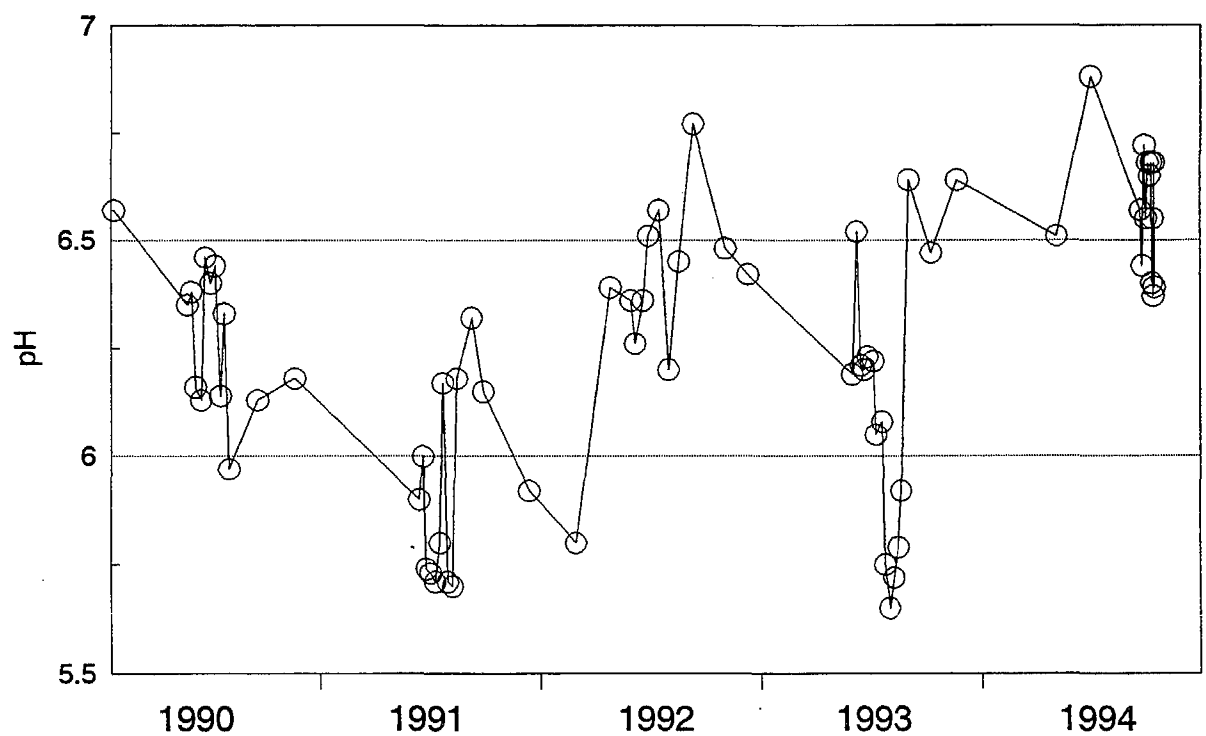


Figure I-102

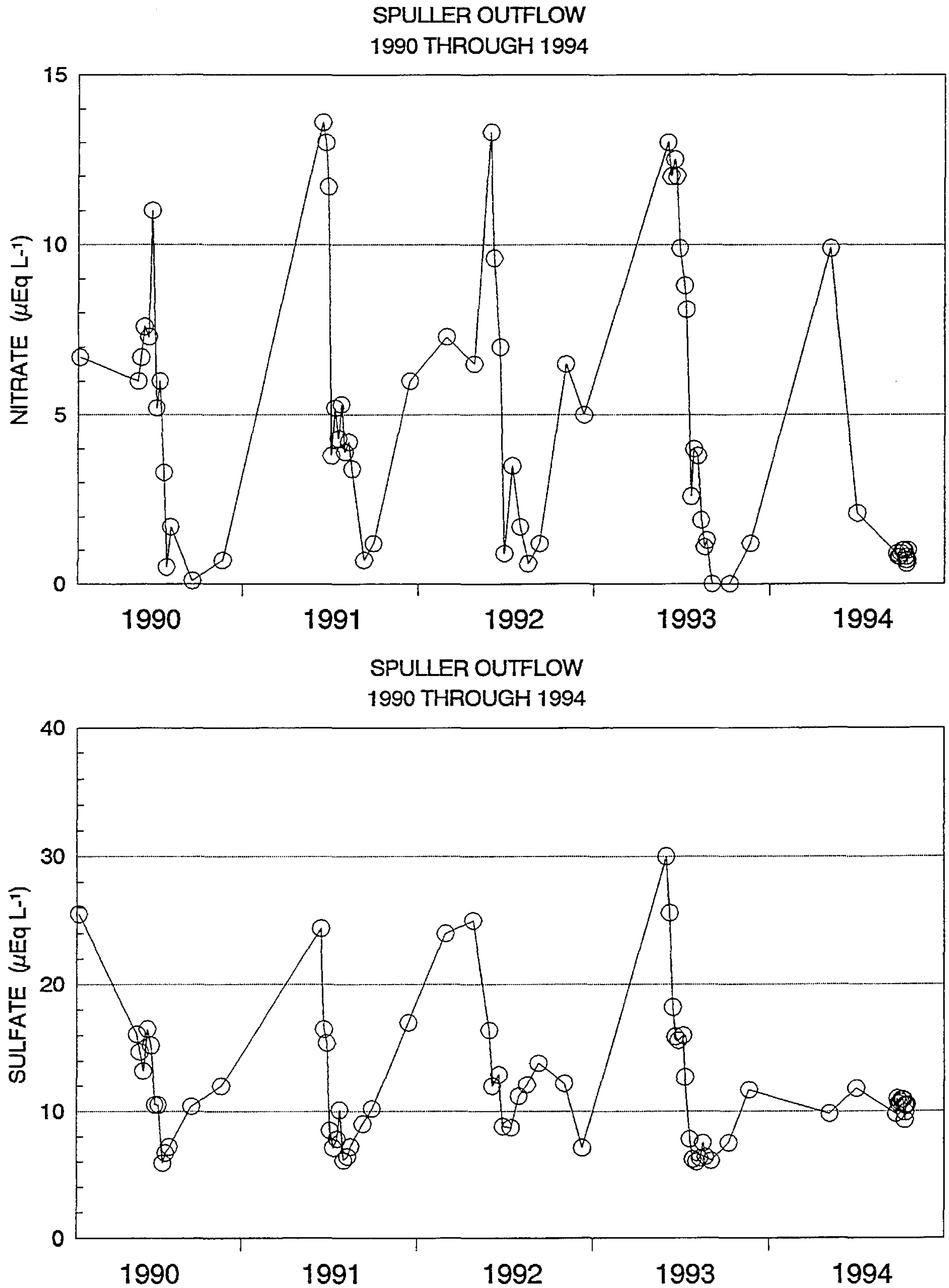
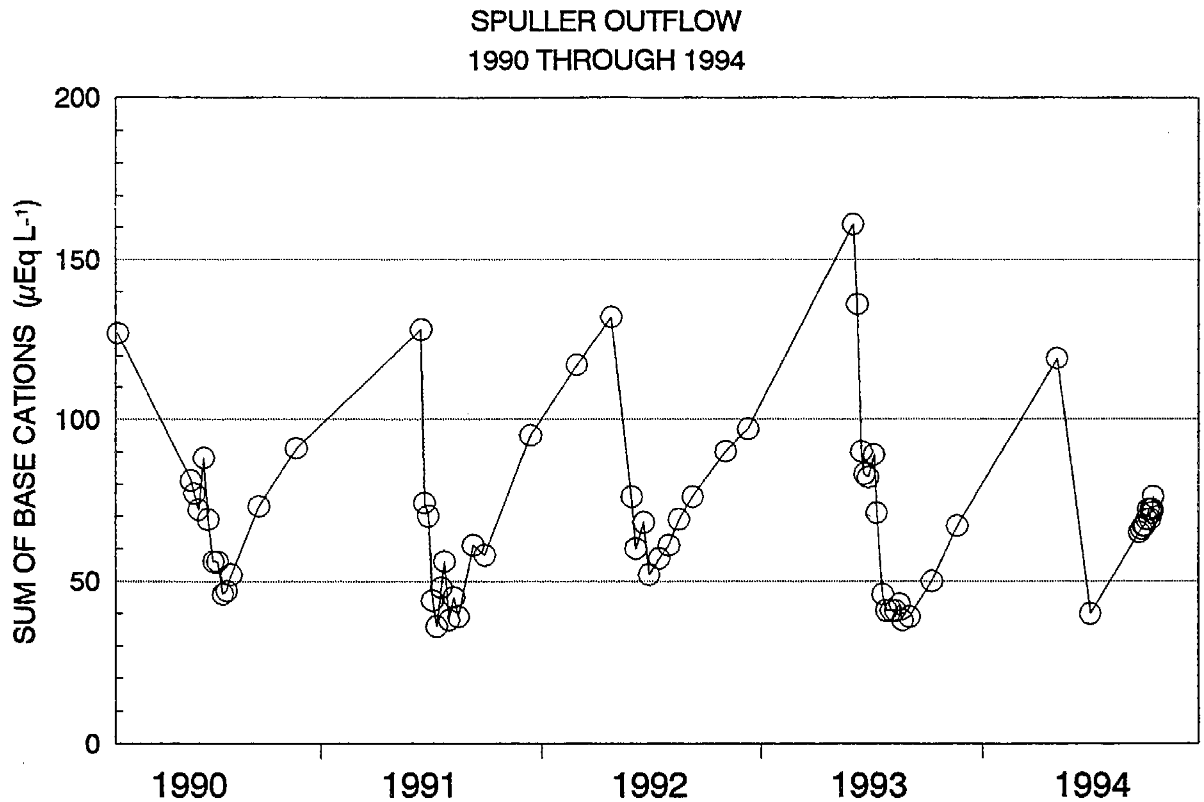

SPULLER OUTFLOW
1990 THROUGH 1994
NITRATE (µEq L-1)
15
10
5
0
1990
1991
1992
1993
1994
SPULLER OUTFLOW
1990 THROUGH 1994
SULFATE (µEq L-1)
40
30
20
10
0
1990
1991
1992
1993
1994

Figure I-103


SPULLER OUTFLOW
1990 THROUGH 1994
SUM OF BASE CATIONS (µEq L-1)
200
150
100
50
0
1990
1991
1992
1993
1994

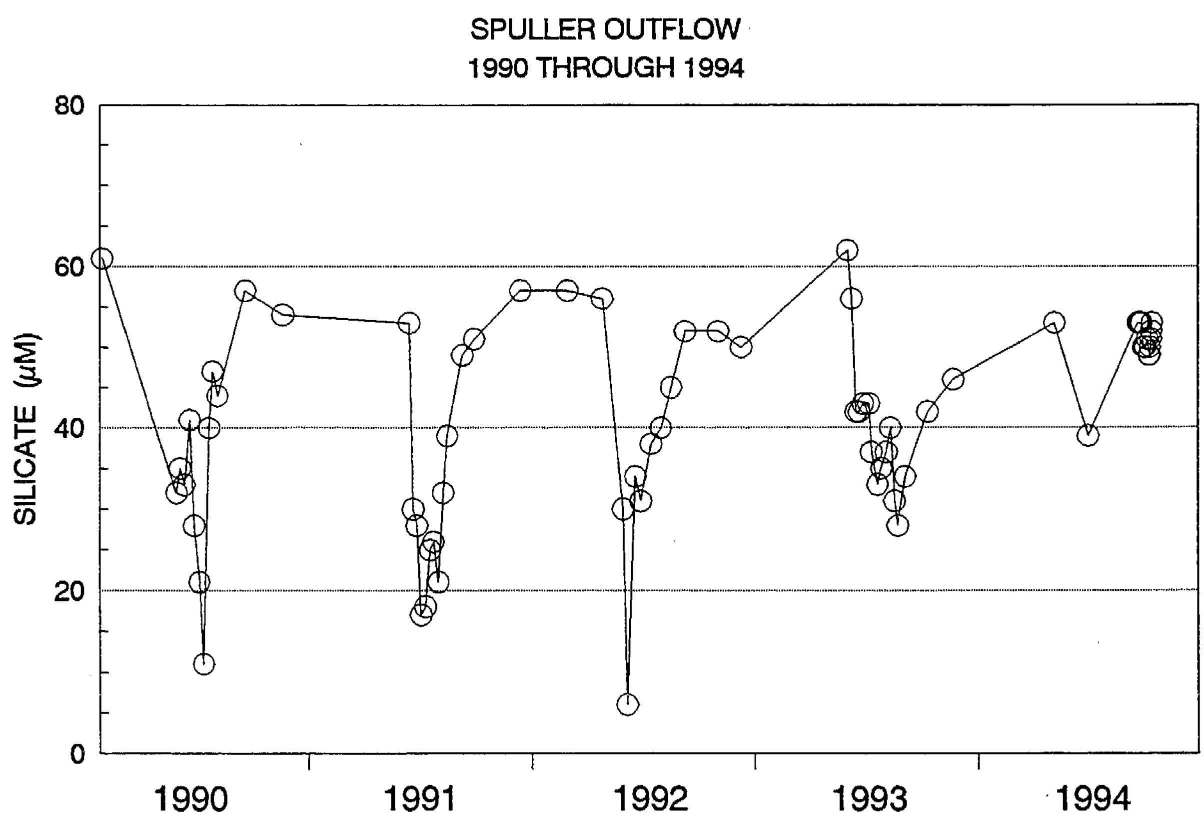
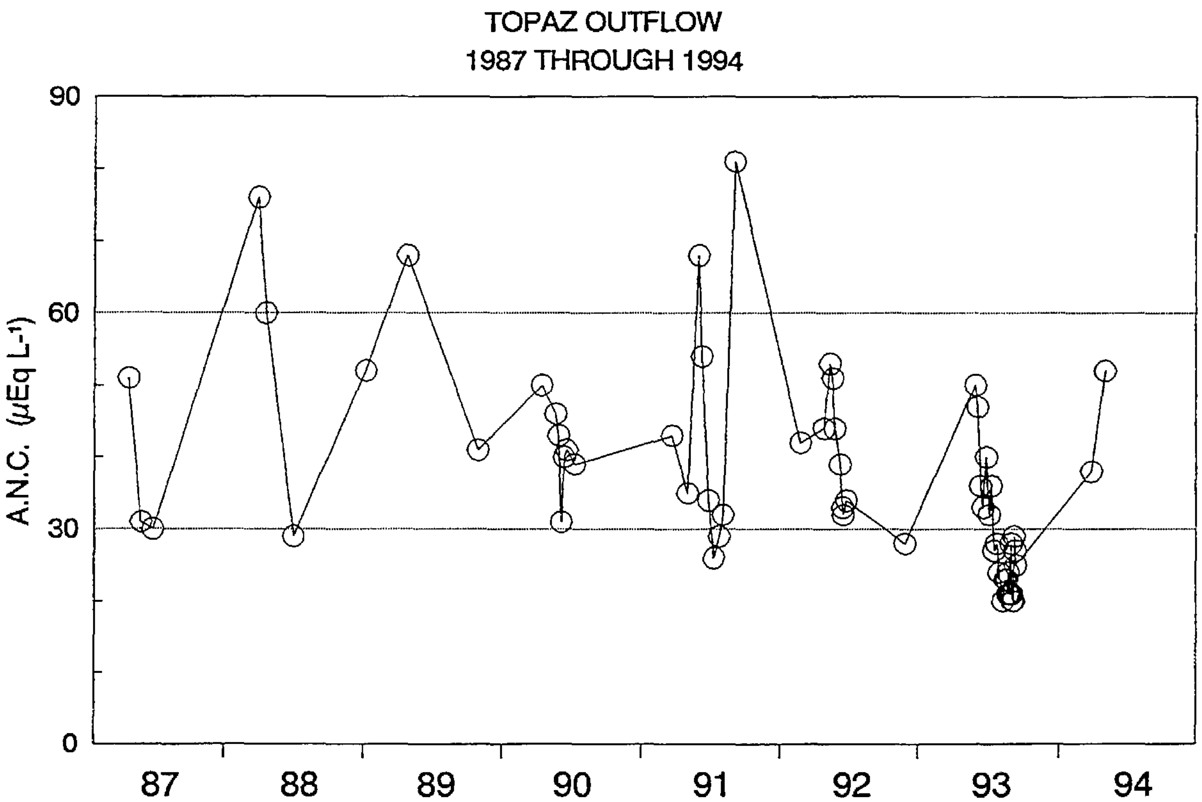

SPULLER OUTFLOW
1990 THROUGH 1994
SILICATE (µM)
80
60
40
20
0
1990
1991
1992
1993
1994

Figure I-104


TOPAZ OUTFLOW
1987 THROUGH 1994
A.N.C. (μEq L^{-1})
90
60
30
0
87
88
89
90
91
92
93
94

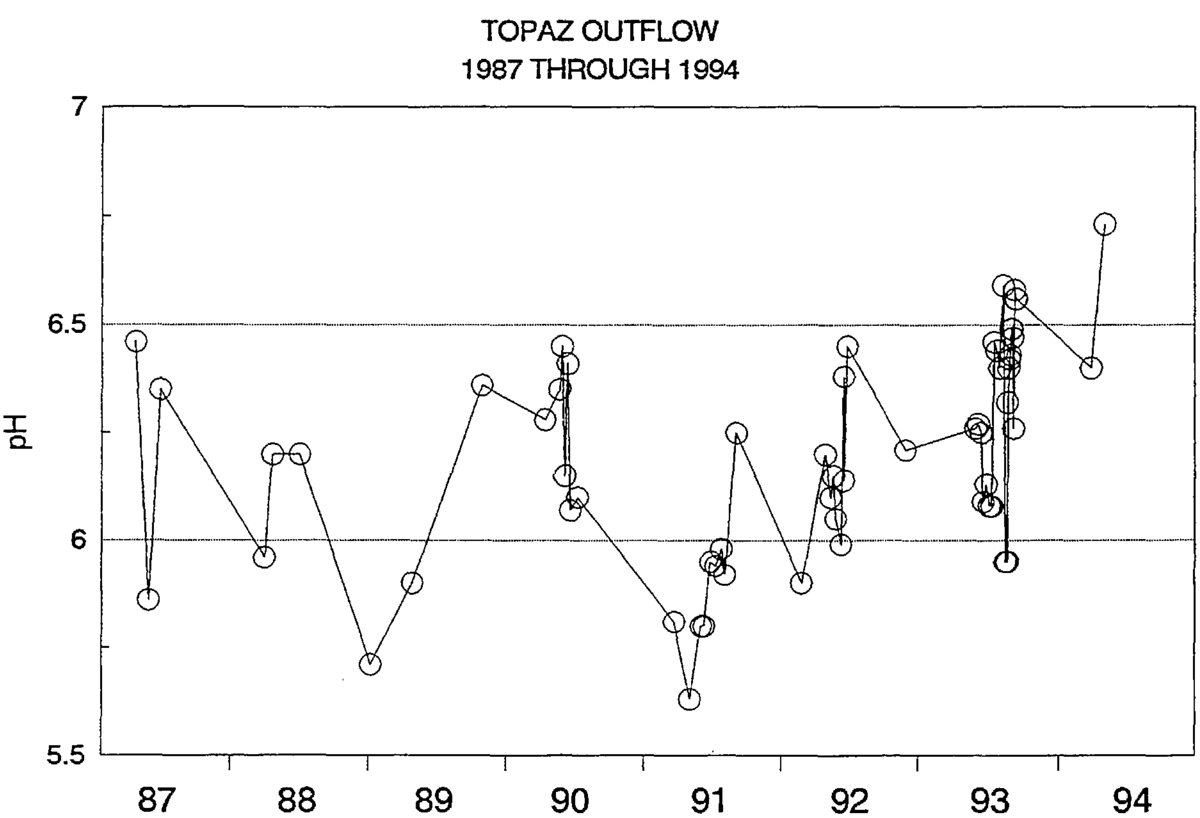
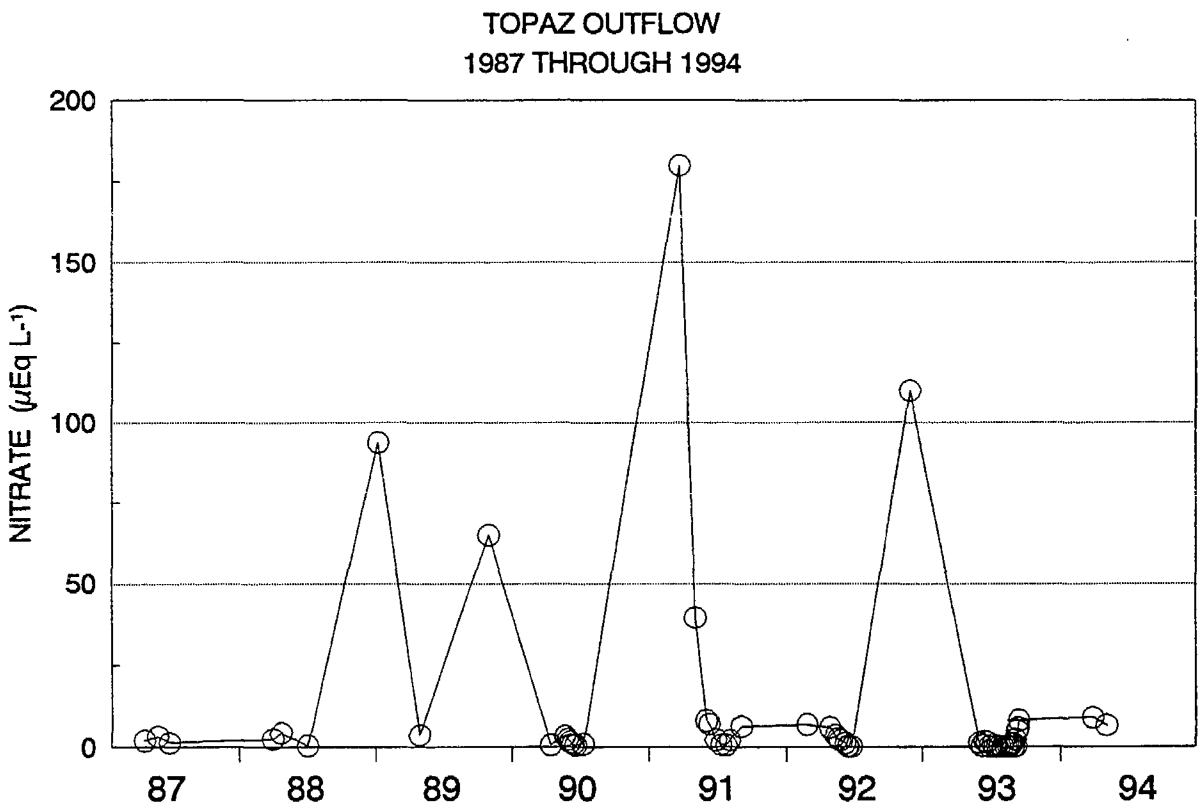
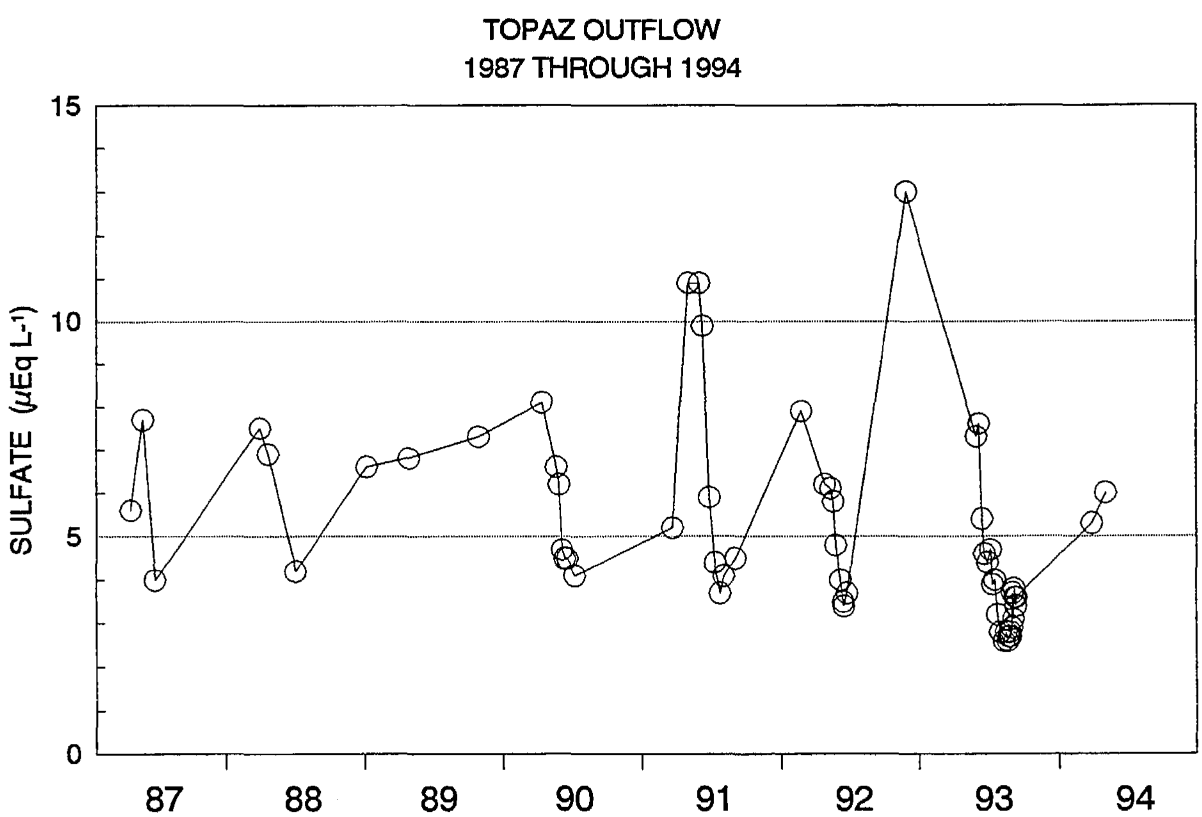

TOPAZ OUTFLOW
1987 THROUGH 1994
pH
7
6.5
6
5.5
87
88
89
90
91
92
93
94

Figure I-105

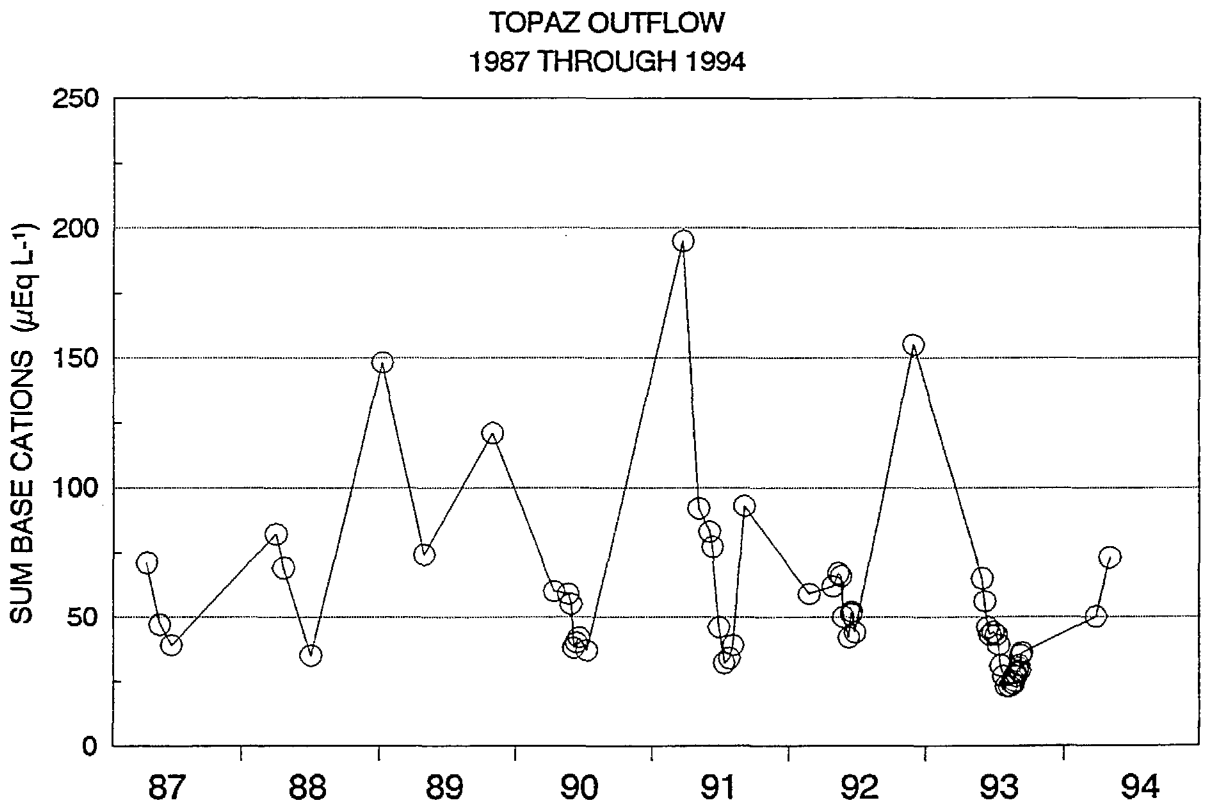


TOPAZ OUTFLOW
1987 THROUGH 1994
NITRATE (μEq L⁻¹)
200
150
100
50
0
87
88
89
90
91
92
93
94



TOPAZ OUTFLOW
1987 THROUGH 1994
SULFATE (μEq L⁻¹)
15
10
5
0
87
88
89
90
91
92
93
94

Figure I-106


TOPAZ OUTFLOW
1987 THROUGH 1994
SUM BASE CATIONS (µEq L-1)
250
200
150
100
50
0
87
88
89
90
91
92
93
94

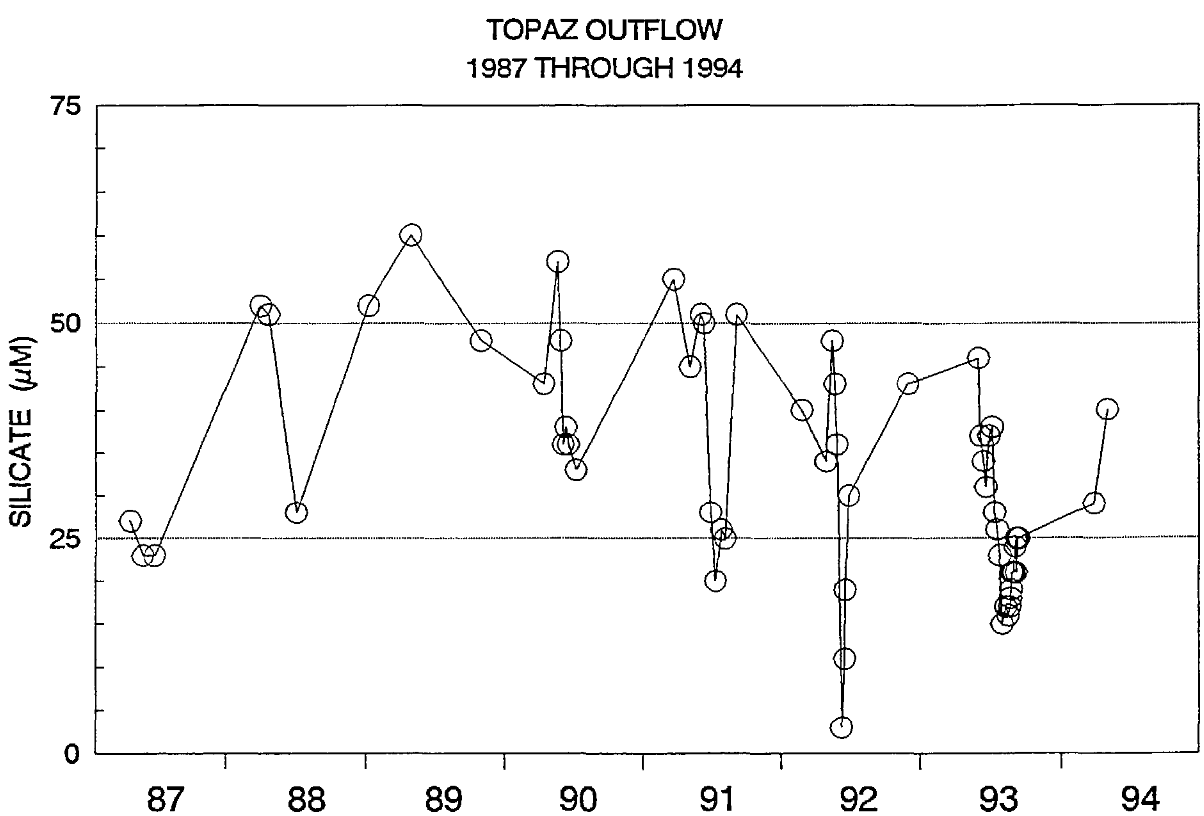
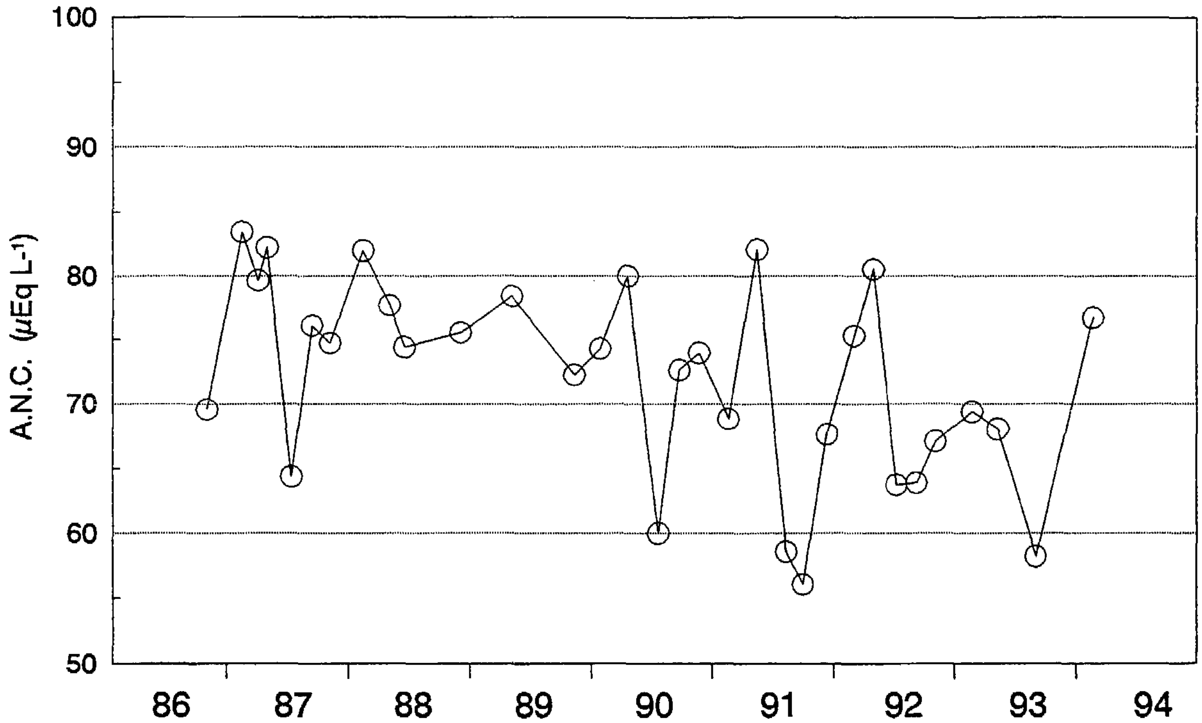

TOPAZ OUTFLOW
1987 THROUGH 1994
SILICATE (µM)
75
50
25
0
87
88
89
90
91
92
93
94

Figure I-107

CRYSTAL LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY



CRYSTAL LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY

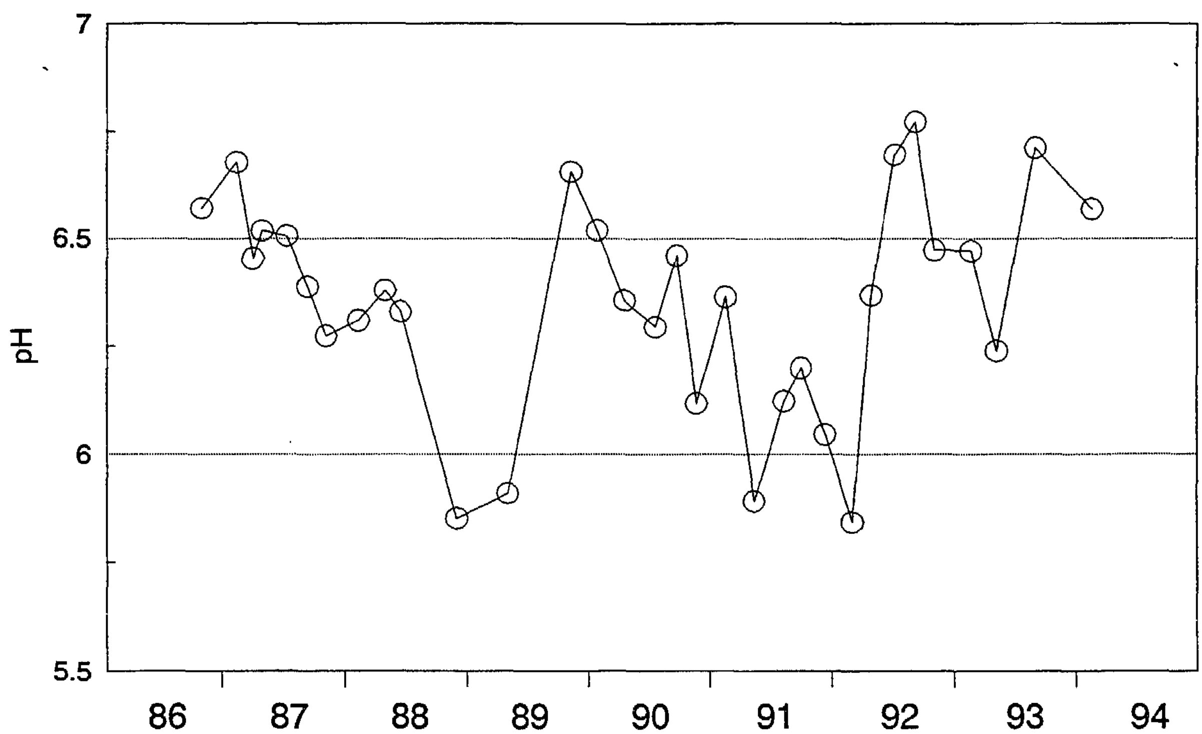
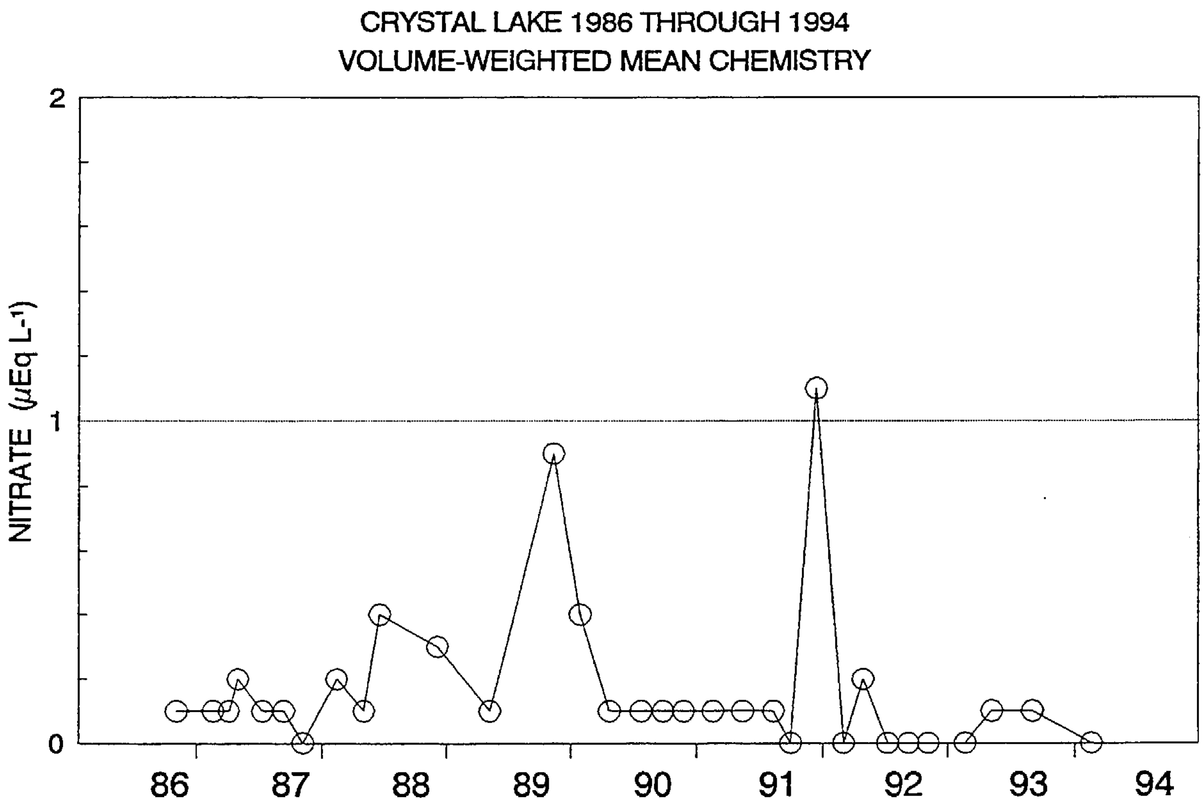
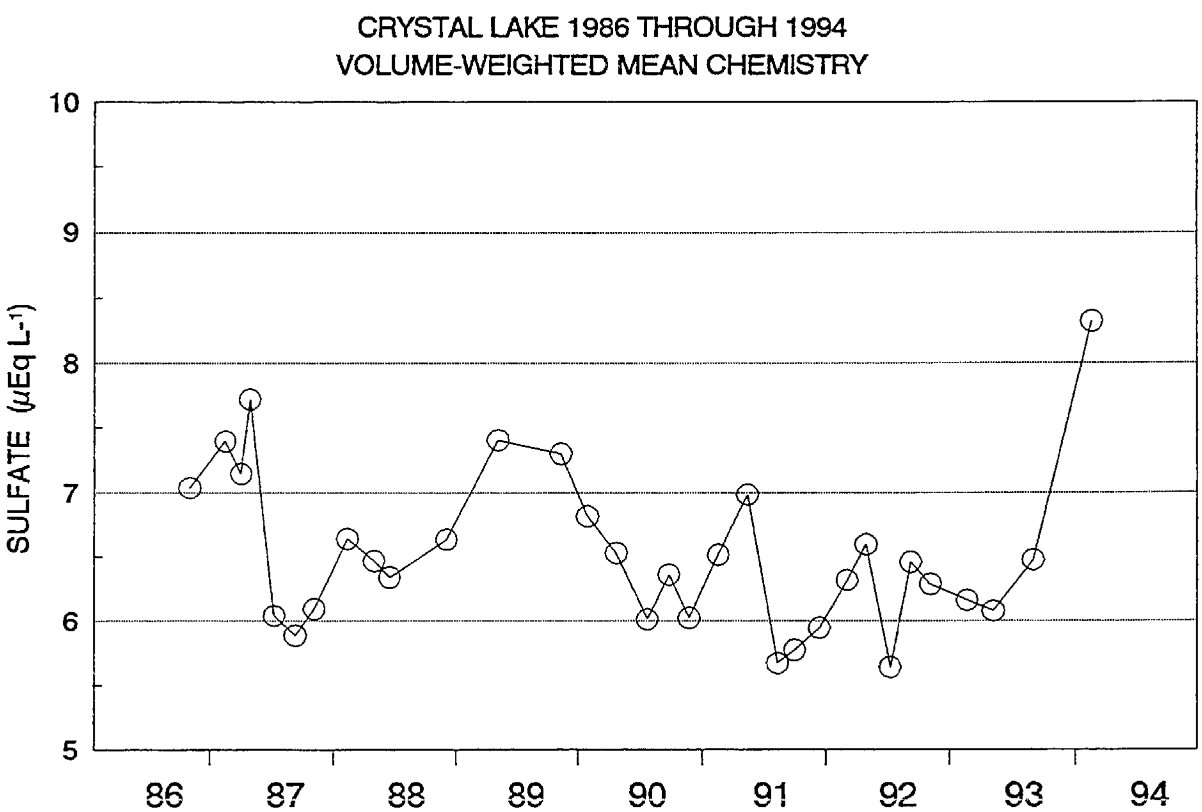


Figure I-108

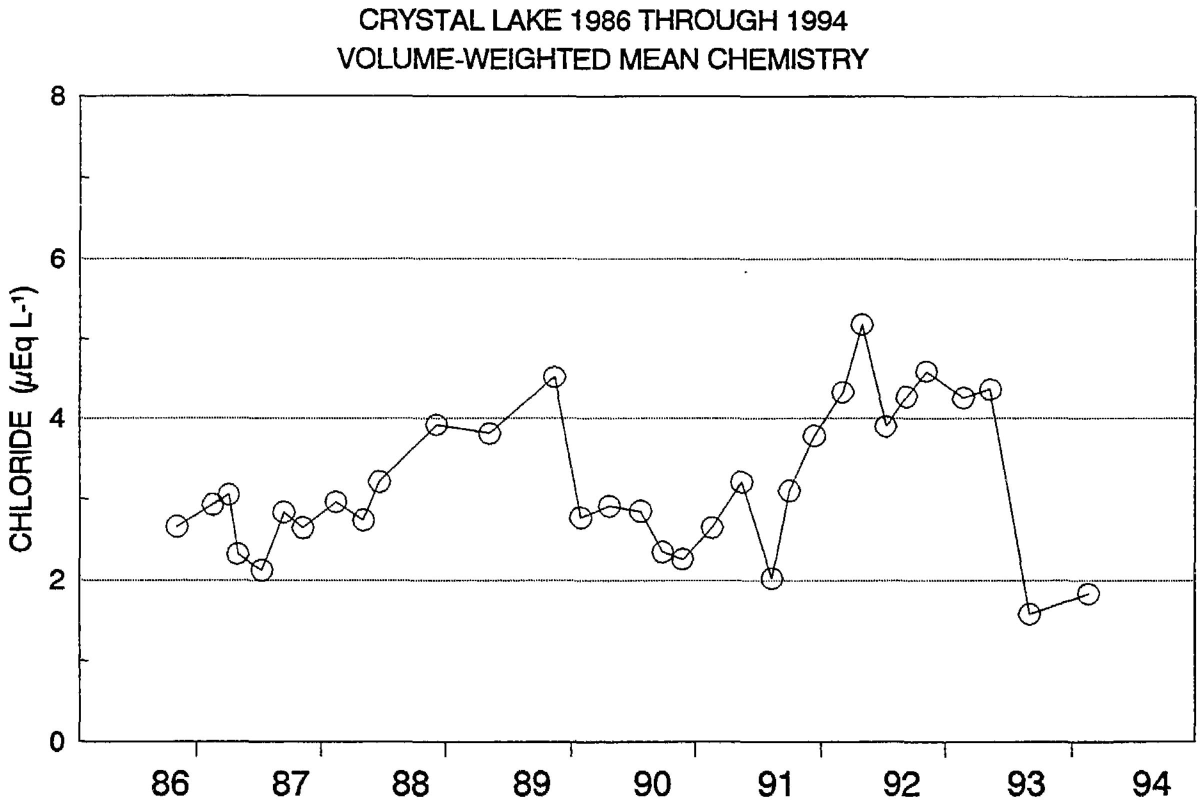


CRYSTAL LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
NITRATE (μEq L^{-1})
0
1
2
86
87
88
89
90
91
92
93
94



CRYSTAL LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
SULFATE (μEq L^{-1})
5
6
7
8
9
10
86
87
88
89
90
91
92
93
94

Figure I-109


CRYSTAL LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
CHLORIDE (μEq L^{-1})
0
2
4
6
8
86
87
88
89
90
91
92
93
94

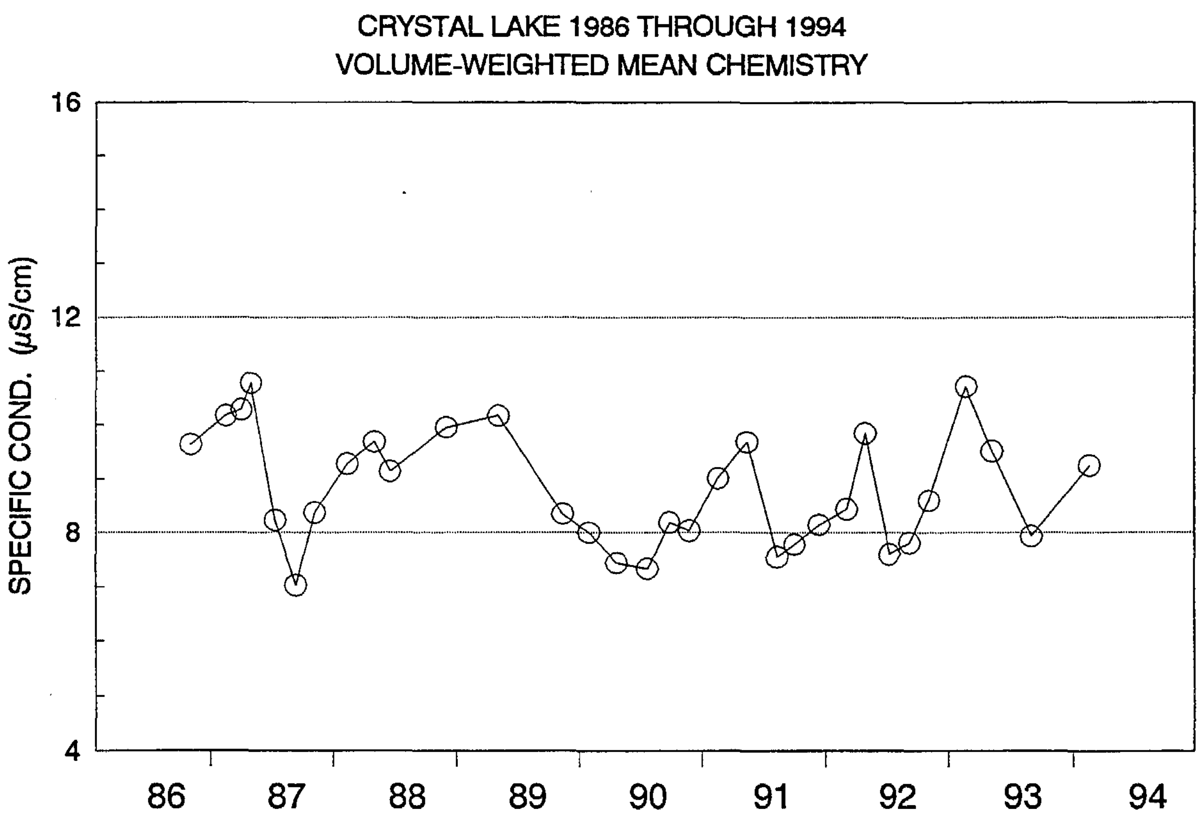
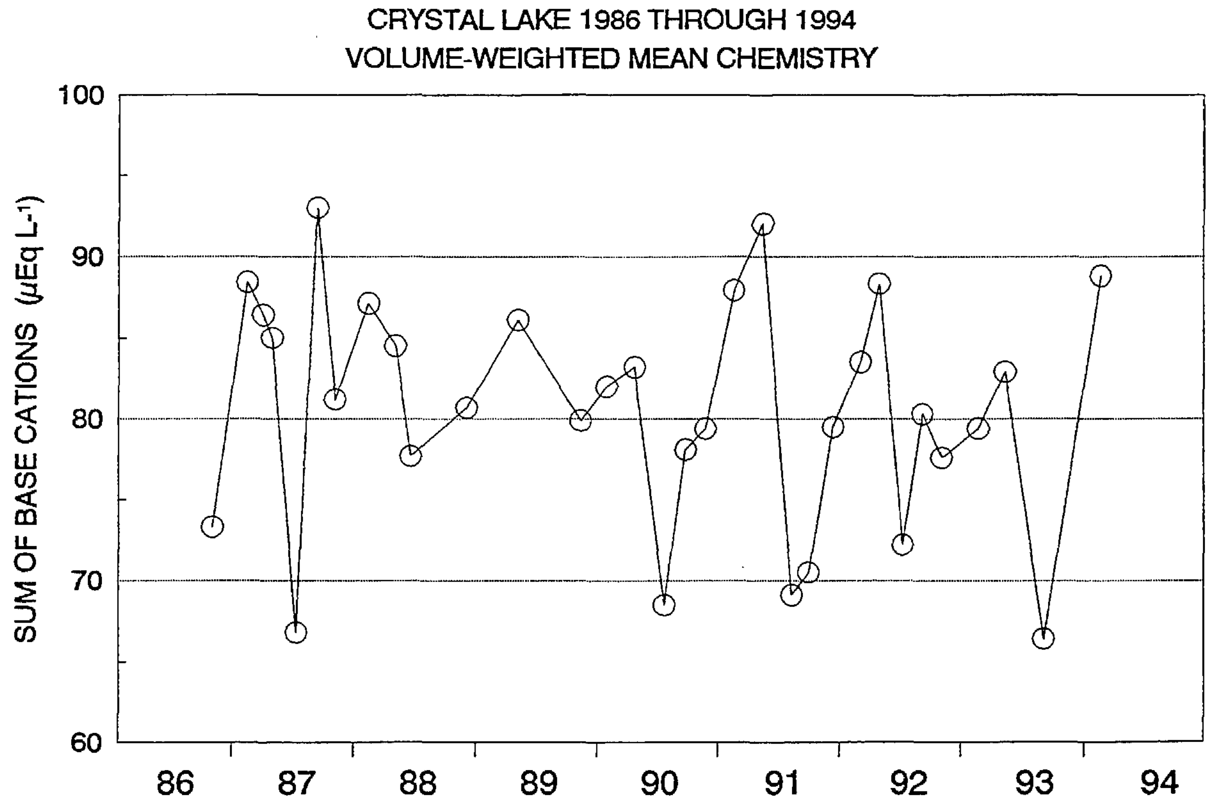

CRYSTAL LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
SPECIFIC COND. (μS/cm)
4
8
12
16
86
87
88
89
90
91
92
93
94

Figure I-110


CRYSTAL LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
SUM OF BASE CATIONS (μEq L^{-1})
100
90
80
70
60
86
87
88
89
90
91
92
93
94

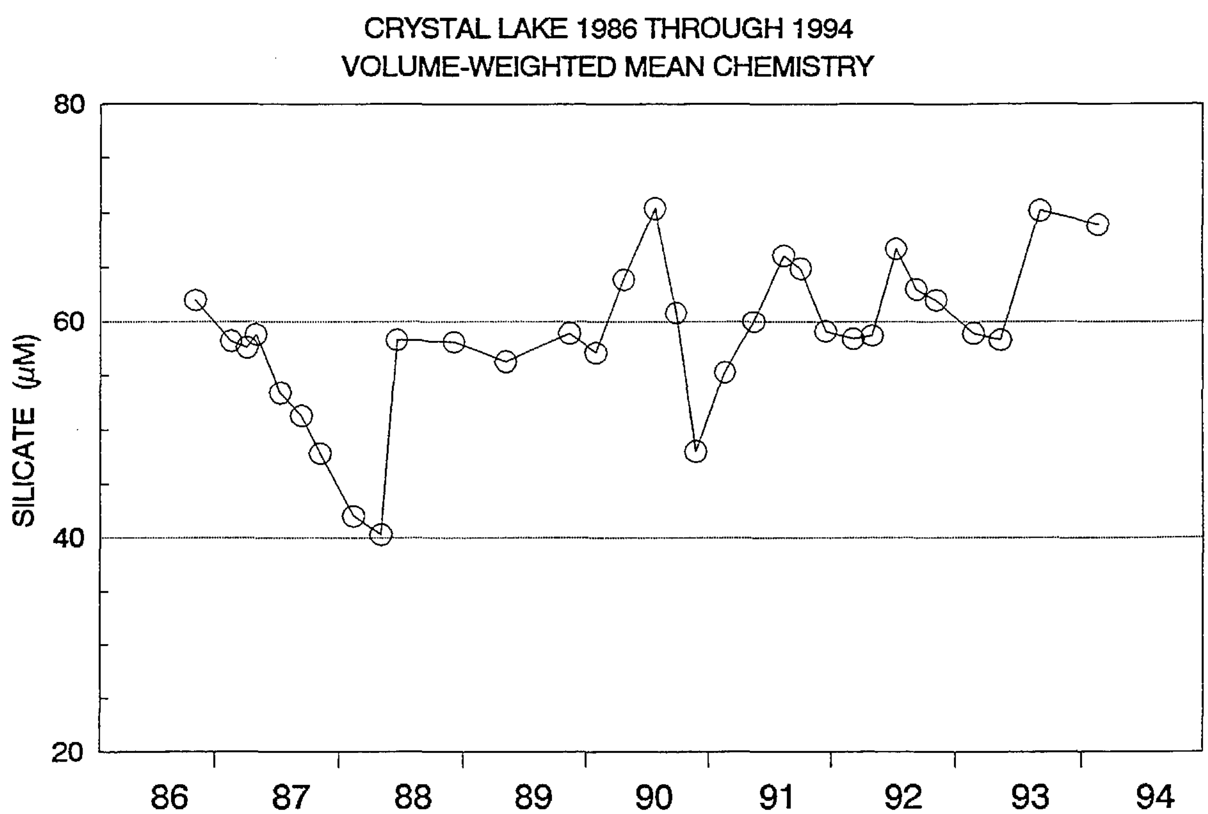
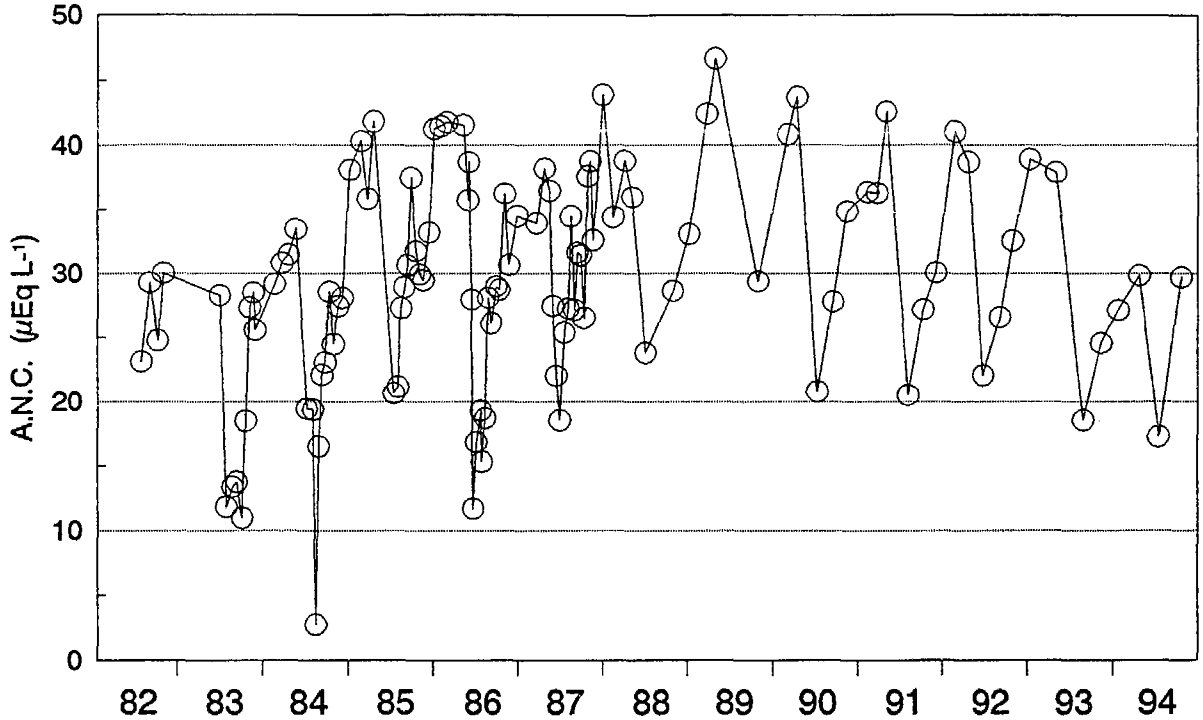

CRYSTAL LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
SILICATE (μM)
80
60
40
20
86
87
88
89
90
91
92
93
94

Figure I-111

EMERALD LAKE 1982 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY



EMERALD LAKE 1982 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY

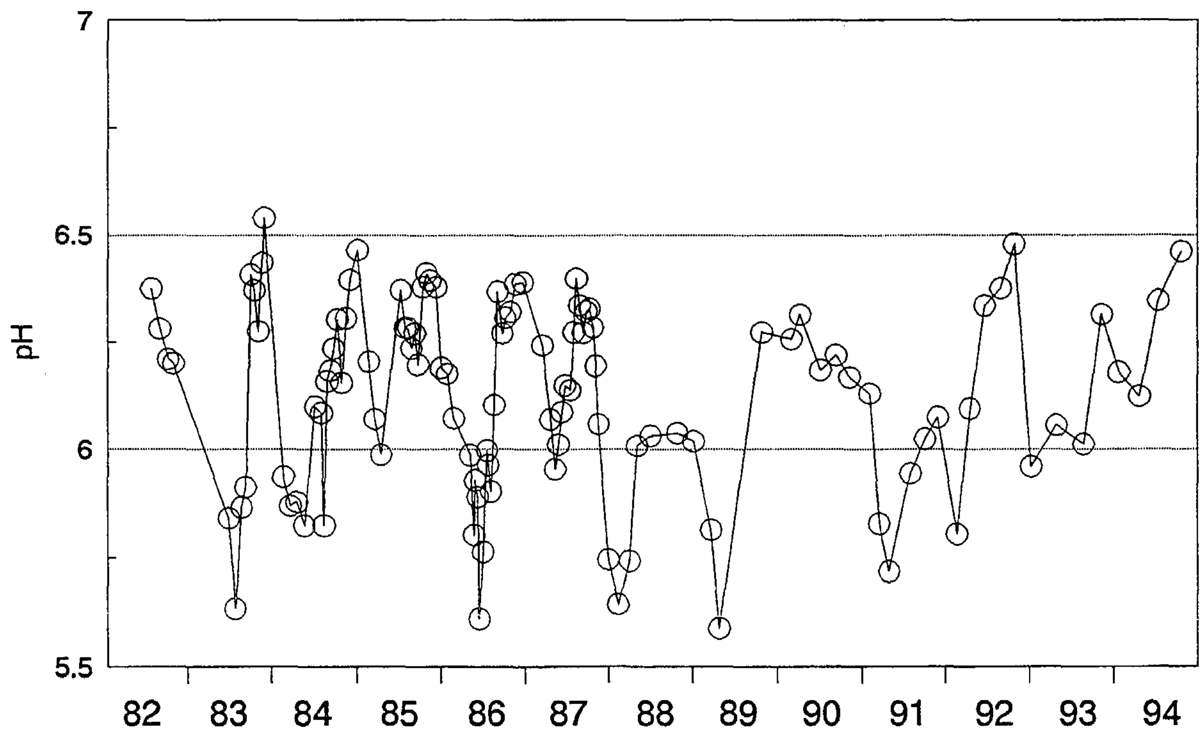
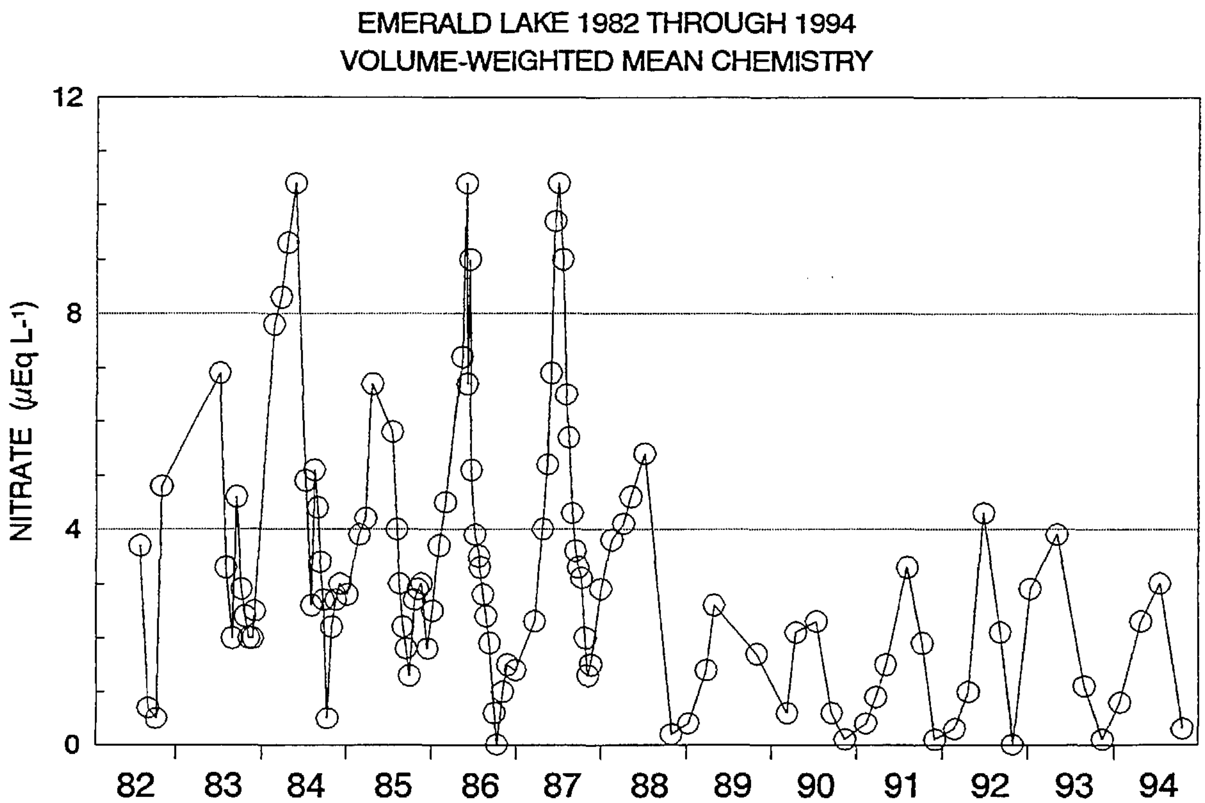


Figure I-112


EMERALD LAKE 1982 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
NITRATE (μEq L^{-1})
12
8
4
0
82
83
84
85
86
87
88
89
90
91
92
93
94

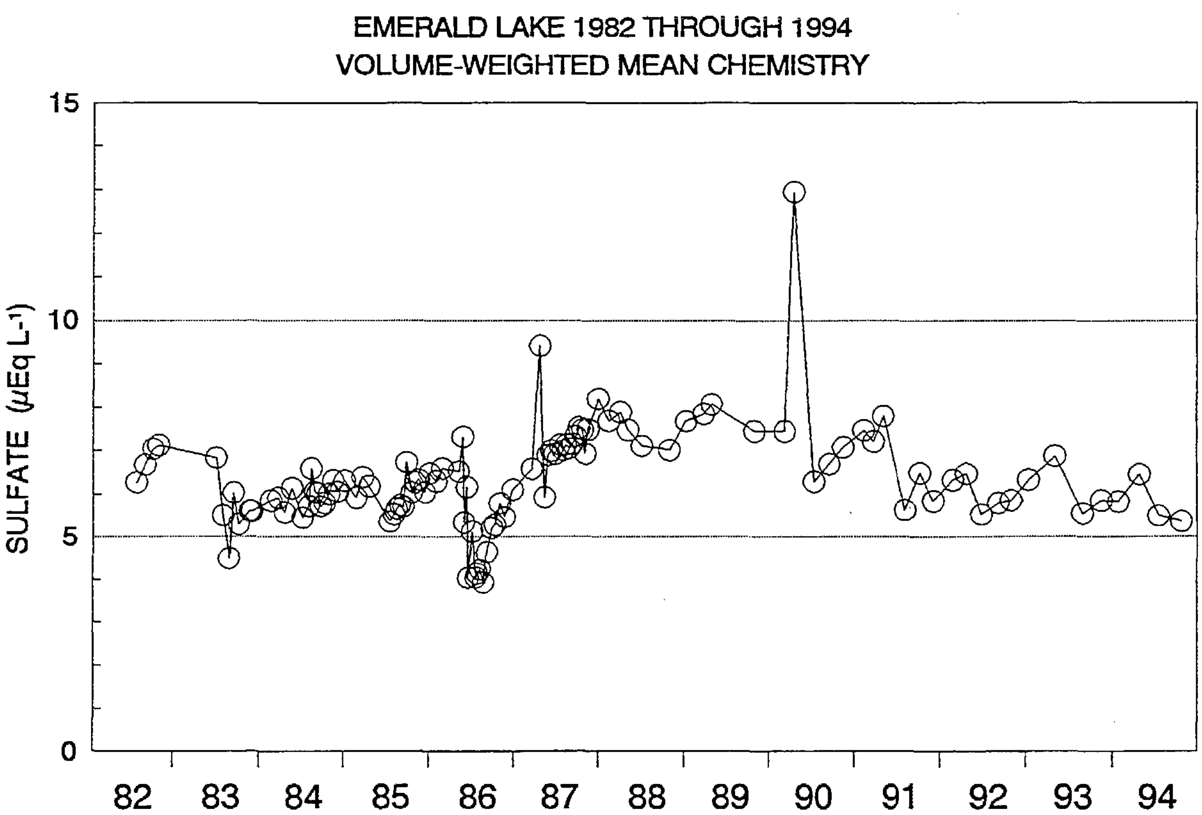
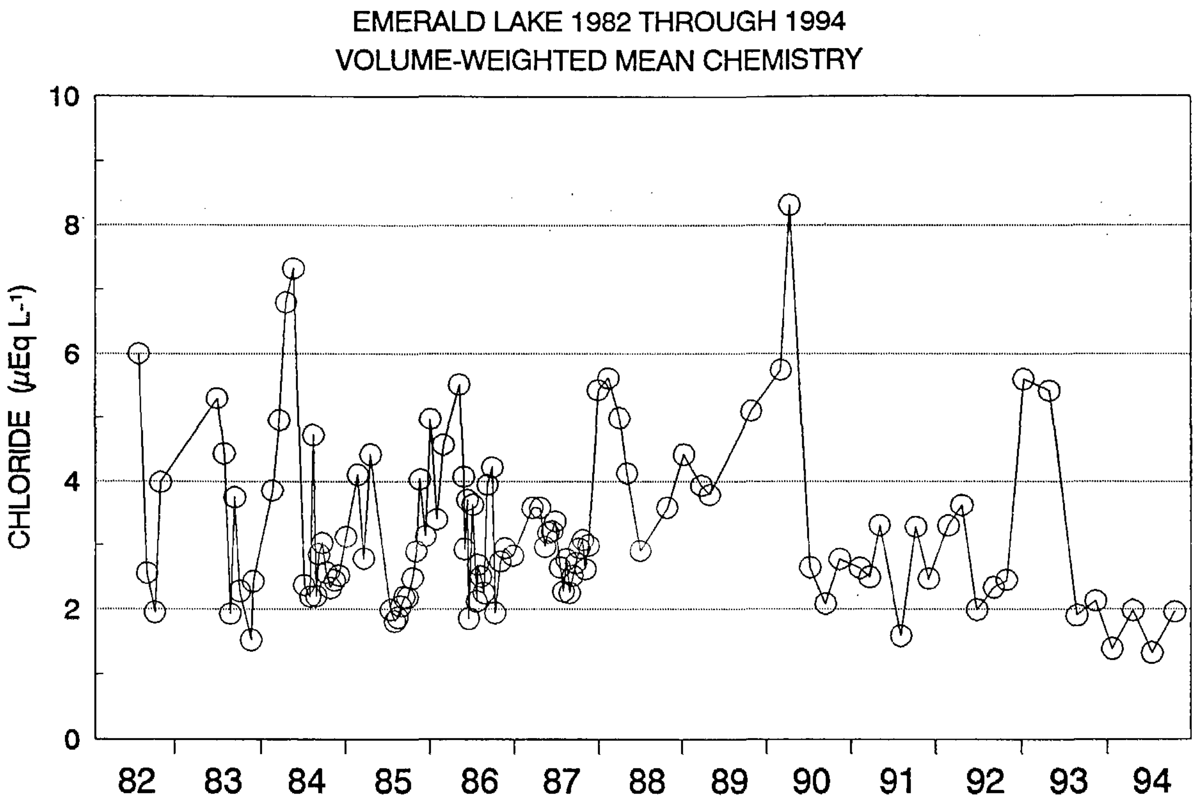

EMERALD LAKE 1982 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
SULFATE (μEq L^{-1})
15
10
5
0
82
83
84
85
86
87
88
89
90
91
92
93
94

Figure I-113


EMERALD LAKE 1982 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
CHLORIDE (μEq L^{-1})
0
2
4
6
8
10
82
83
84
85
86
87
88
89
90
91
92
93
94

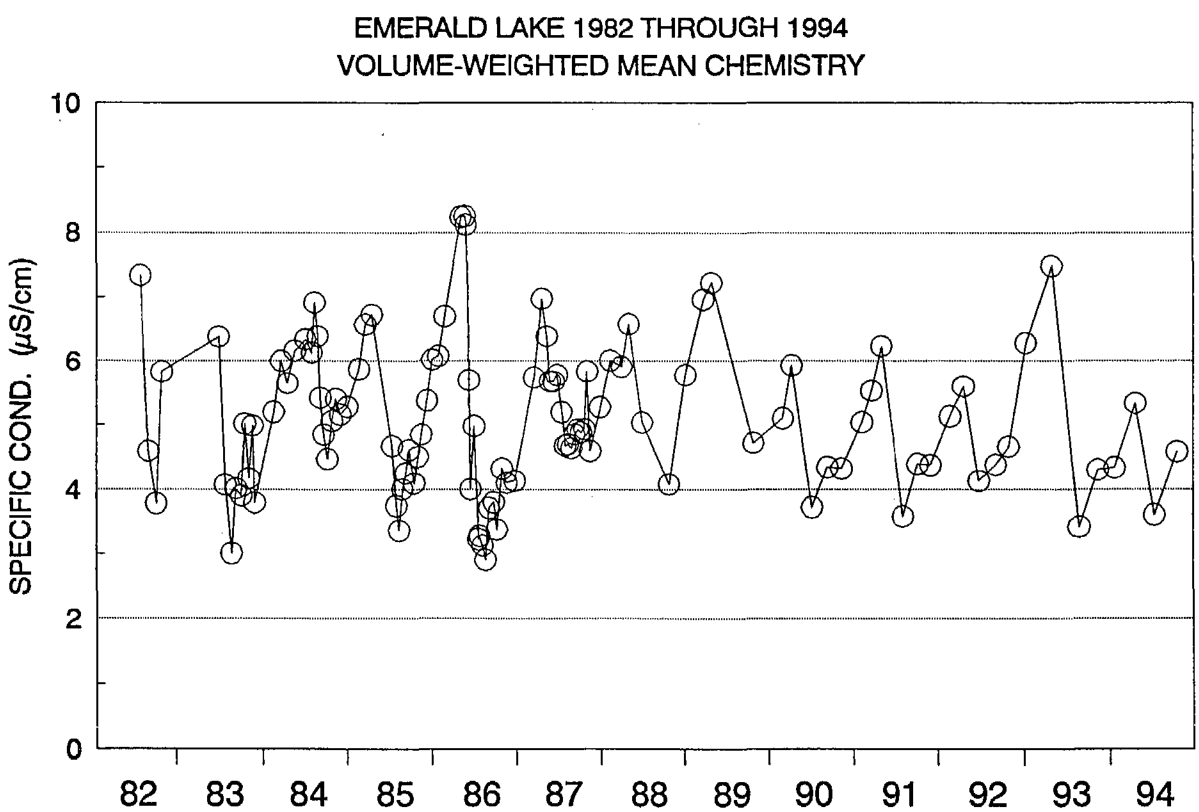
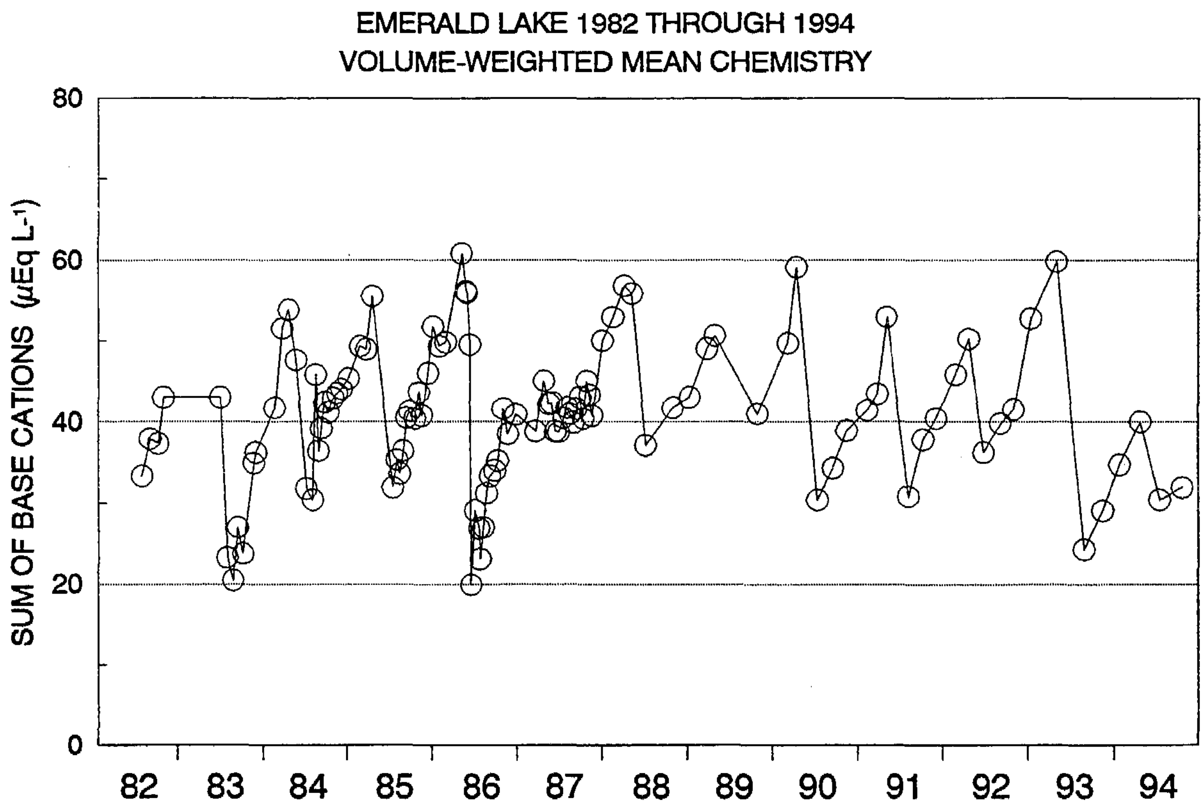

EMERALD LAKE 1982 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
SPECIFIC COND. (μS/cm)
0
2
4
6
8
10
82
83
84
85
86
87
88
89
90
91
92
93
94

Figure I-114


EMERALD LAKE 1982 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
SUM OF BASE CATIONS (μEq L^{-1})
0
20
40
60
80
82 83 84 85 86 87 88 89 90 91 92 93 94

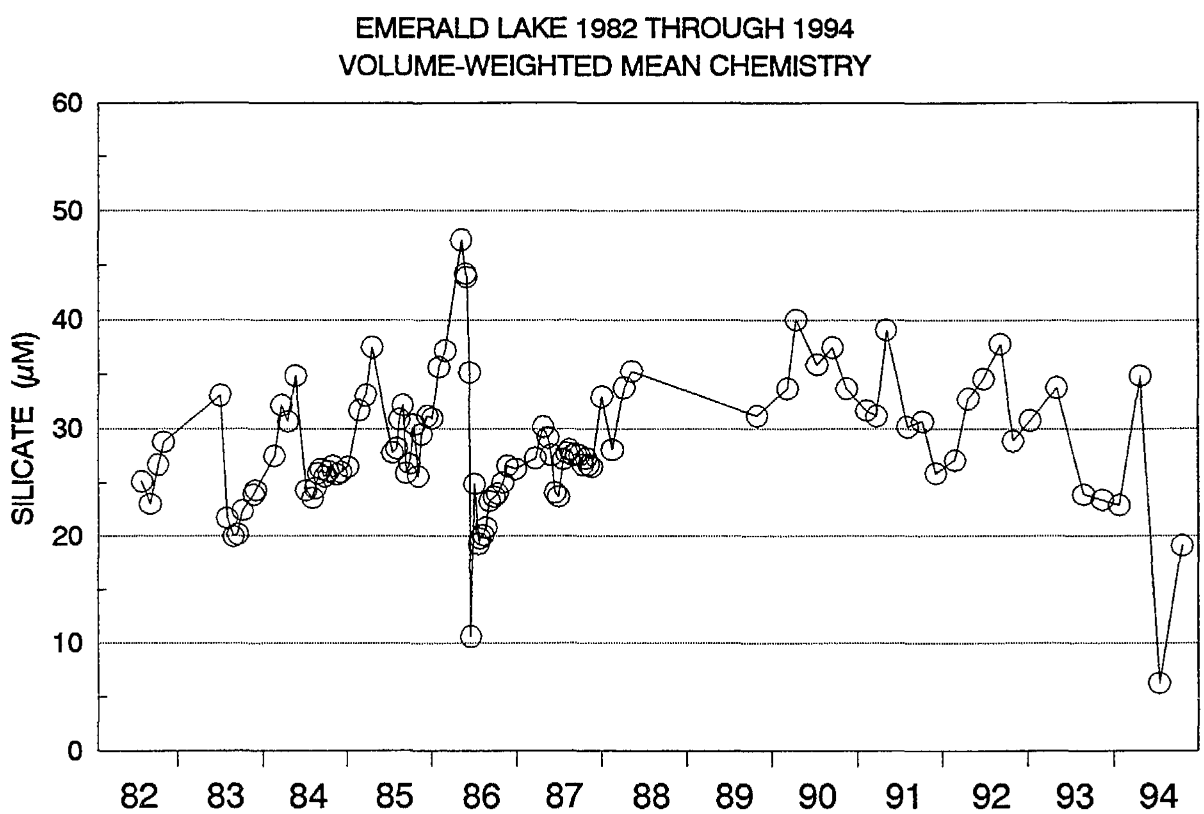
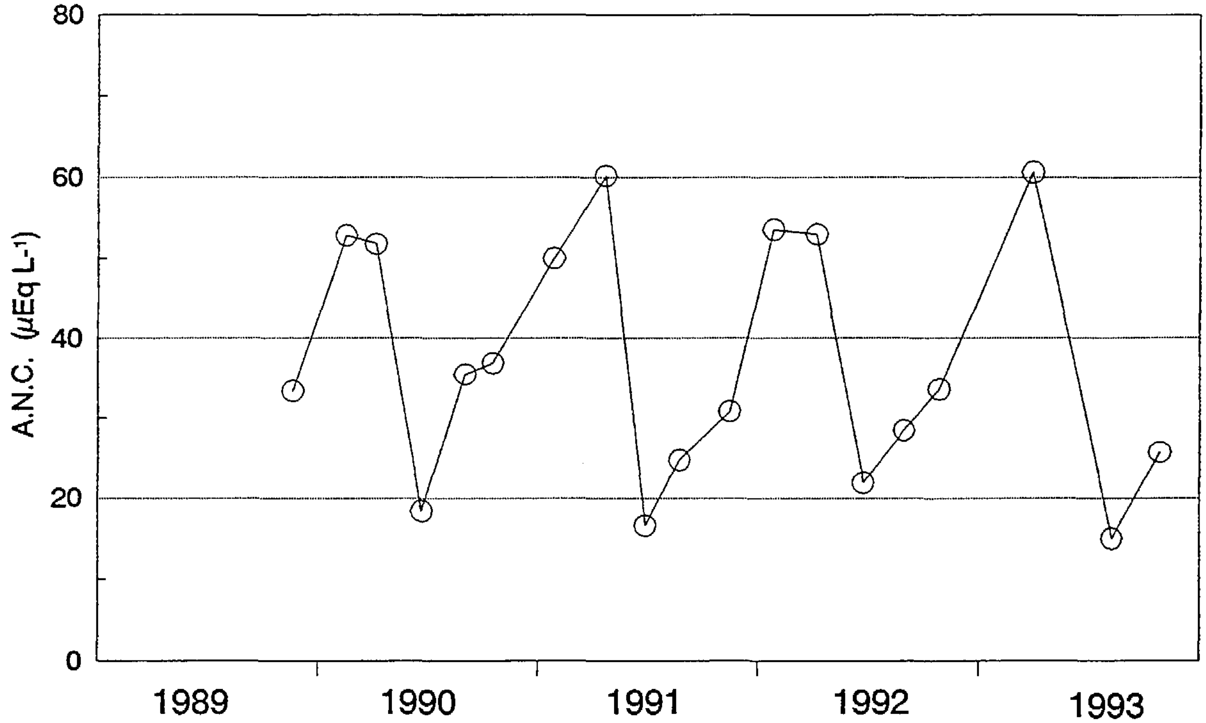

EMERALD LAKE 1982 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
SILICATE (μM)
0
10
20
30
40
50
60
82 83 84 85 86 87 88 89 90 91 92 93 94

Figure I-115

LOST LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY



LOST LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY

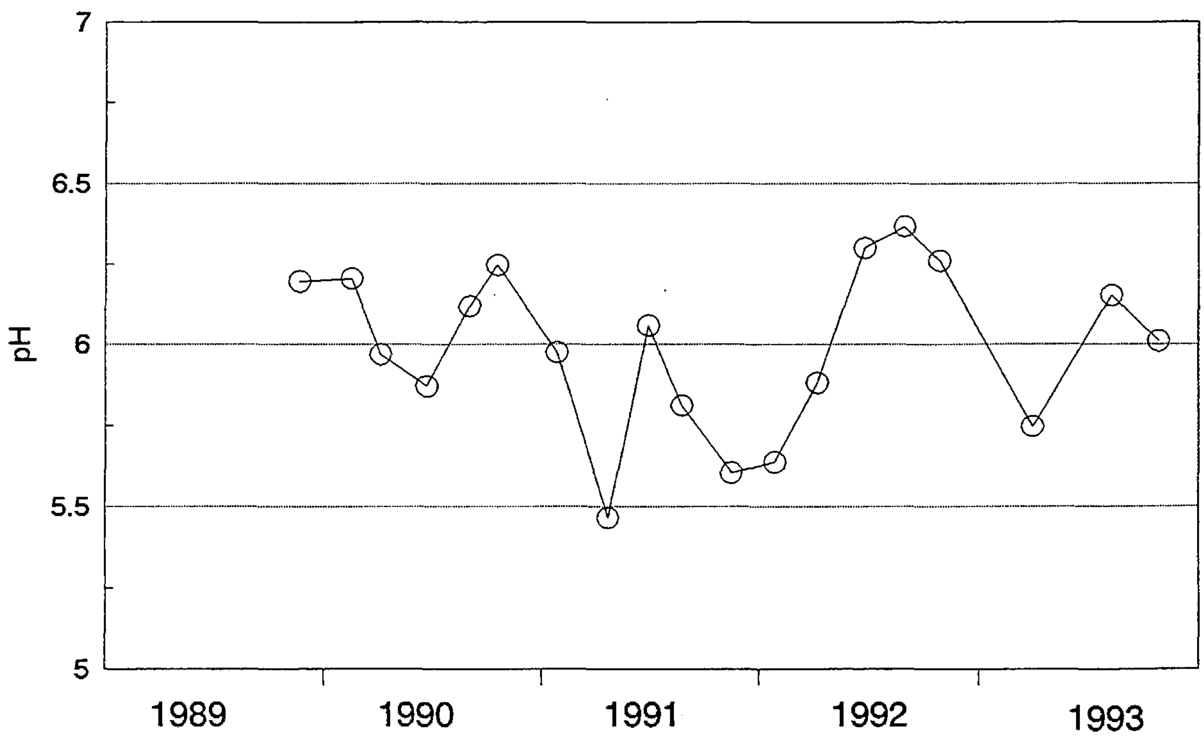
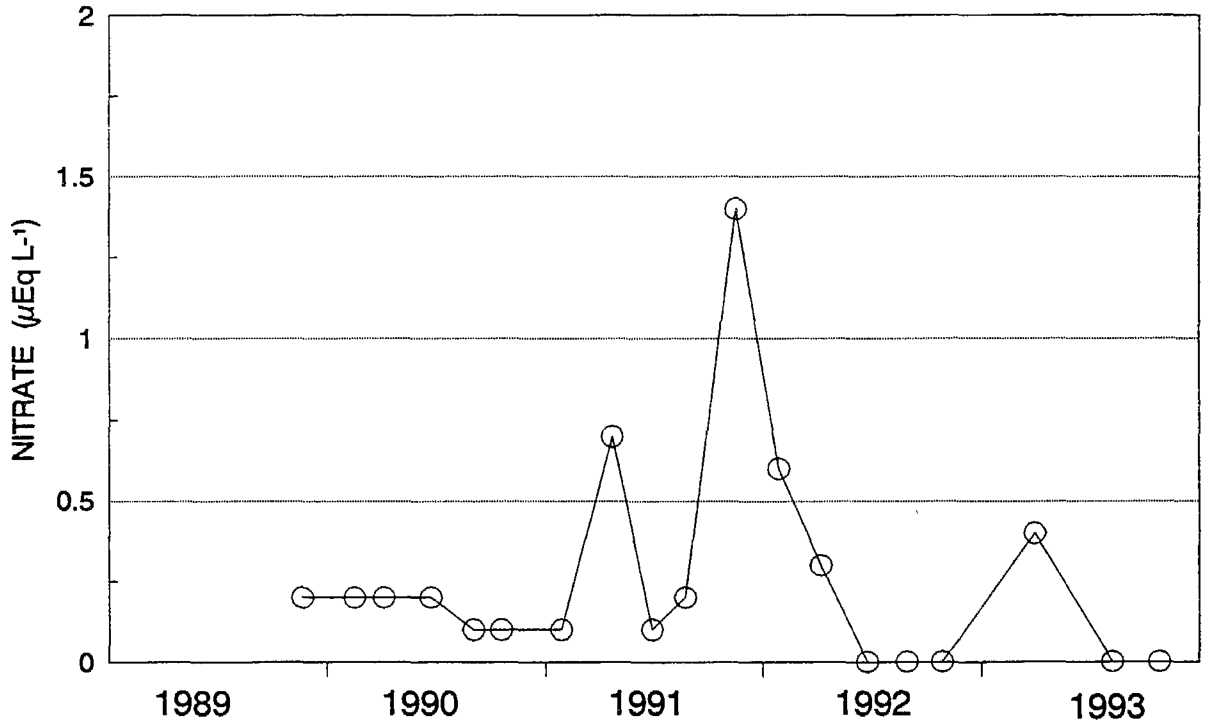


Figure I-116

LOST LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY



LOST LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY

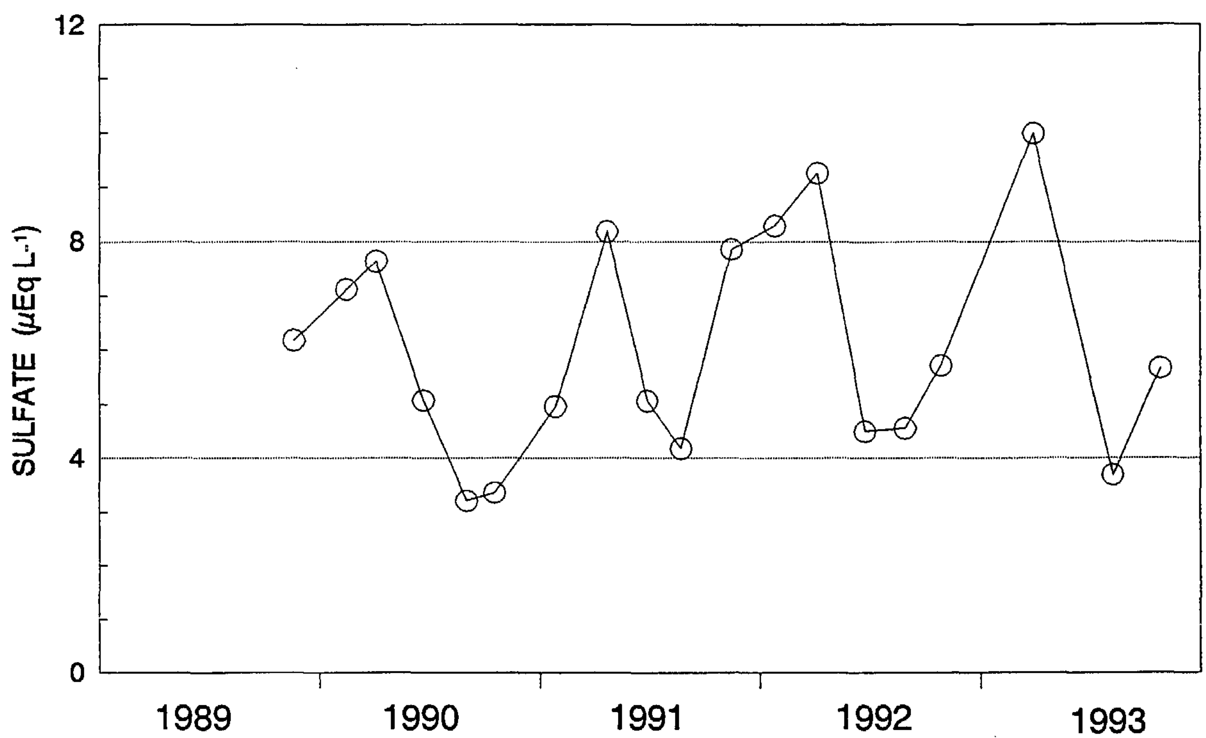
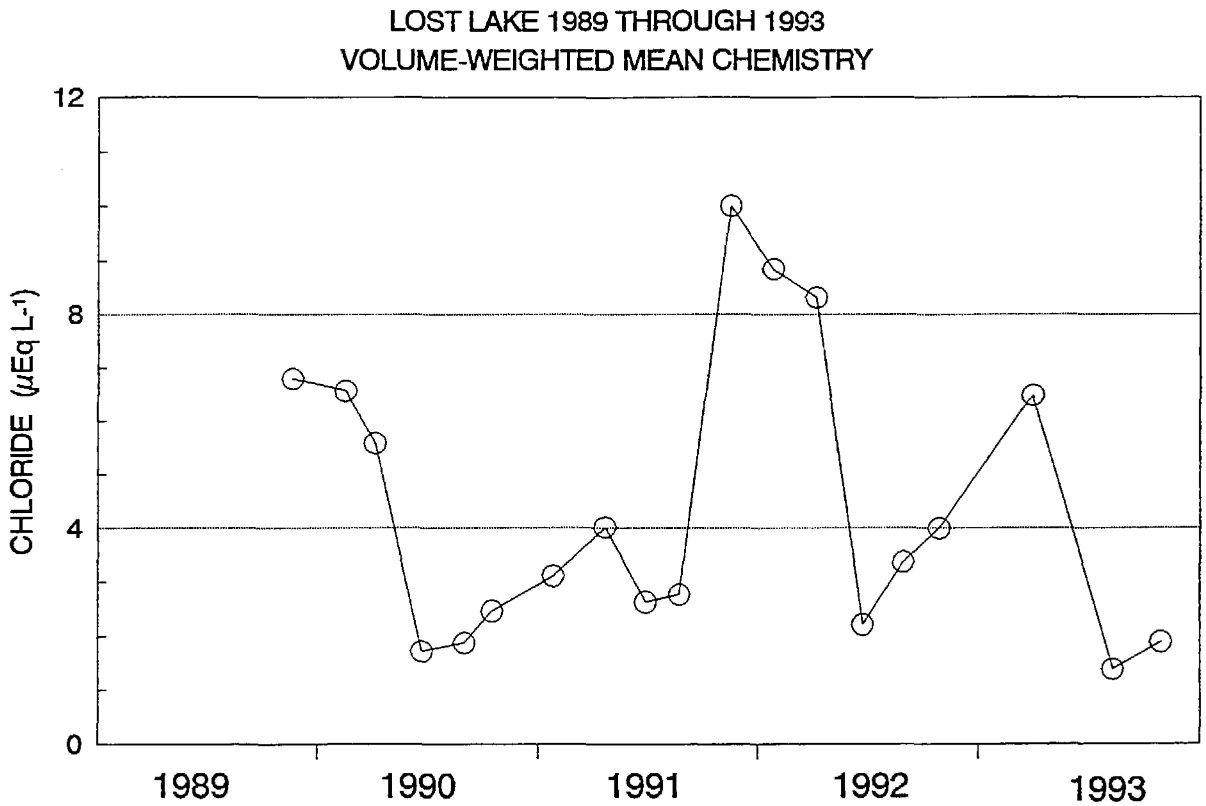
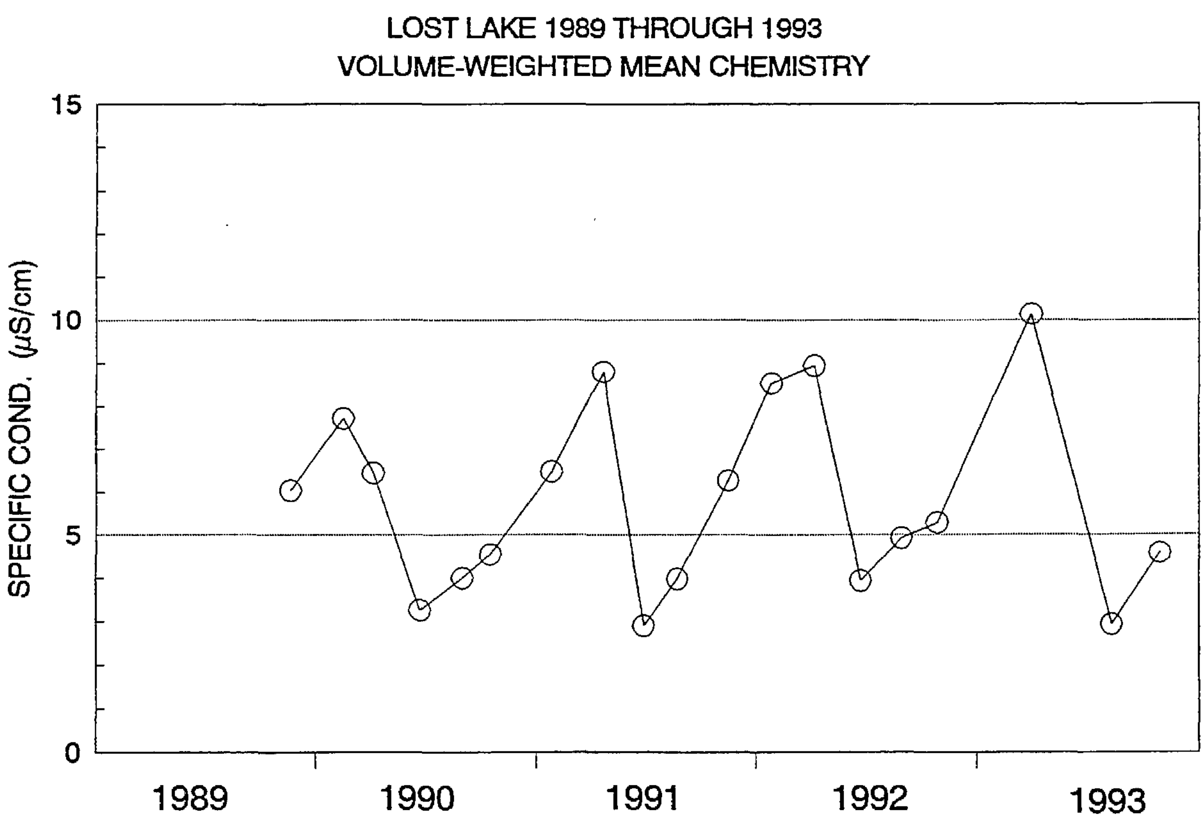


Figure I-117



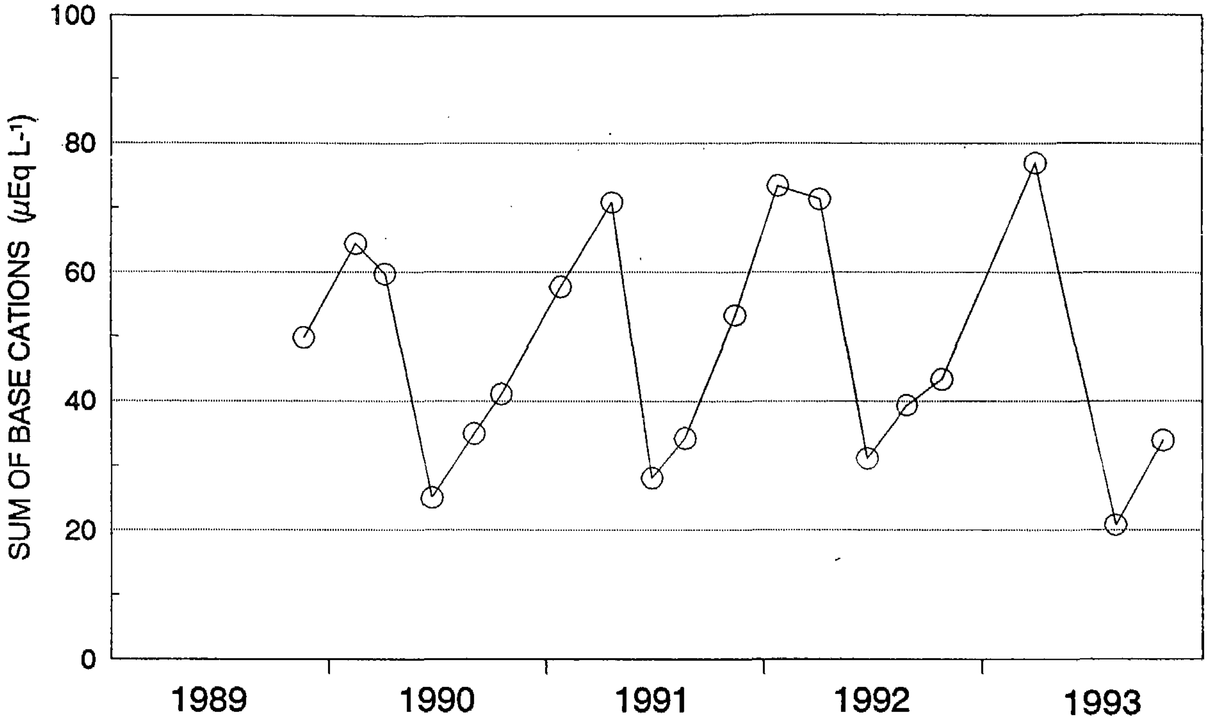
LOST LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
CHLORIDE (μEq L-1)
12
8
4
0
1989
1990
1991
1992
1993



LOST LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
SPECIFIC COND. (μS/cm)
15
10
5
0
1989
1990
1991
1992
1993

Figure I-118

LOST LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY



LOST LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY

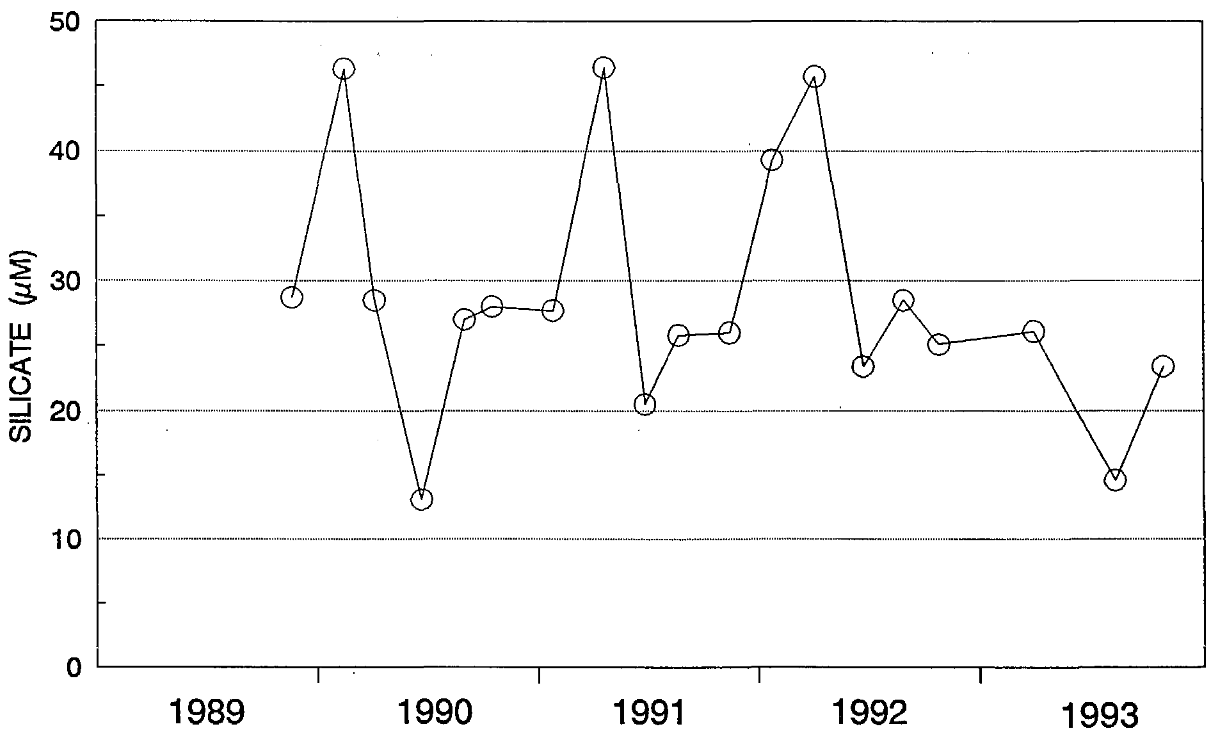
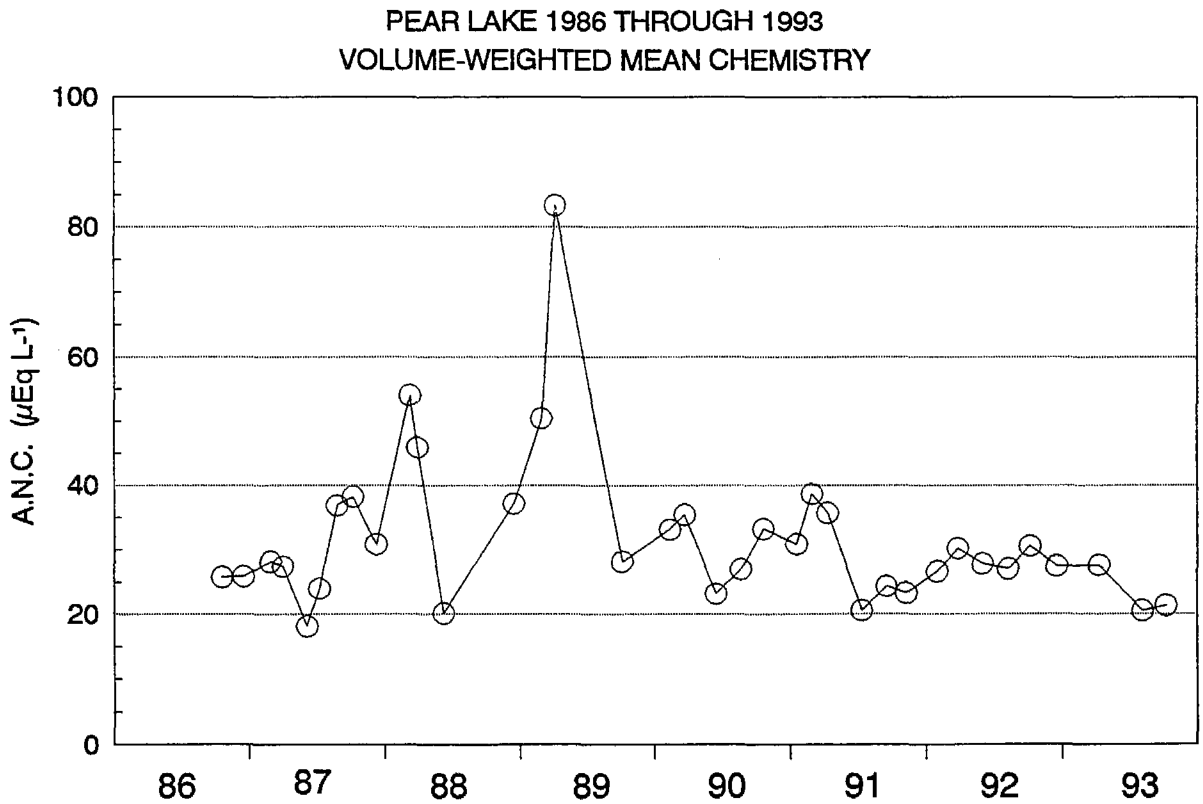


Figure I-119


PEAR LAKE 1986 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
A.N.C. (μEq L-1)
100
80
60
40
20
0
86
87
88
89
90
91
92
93

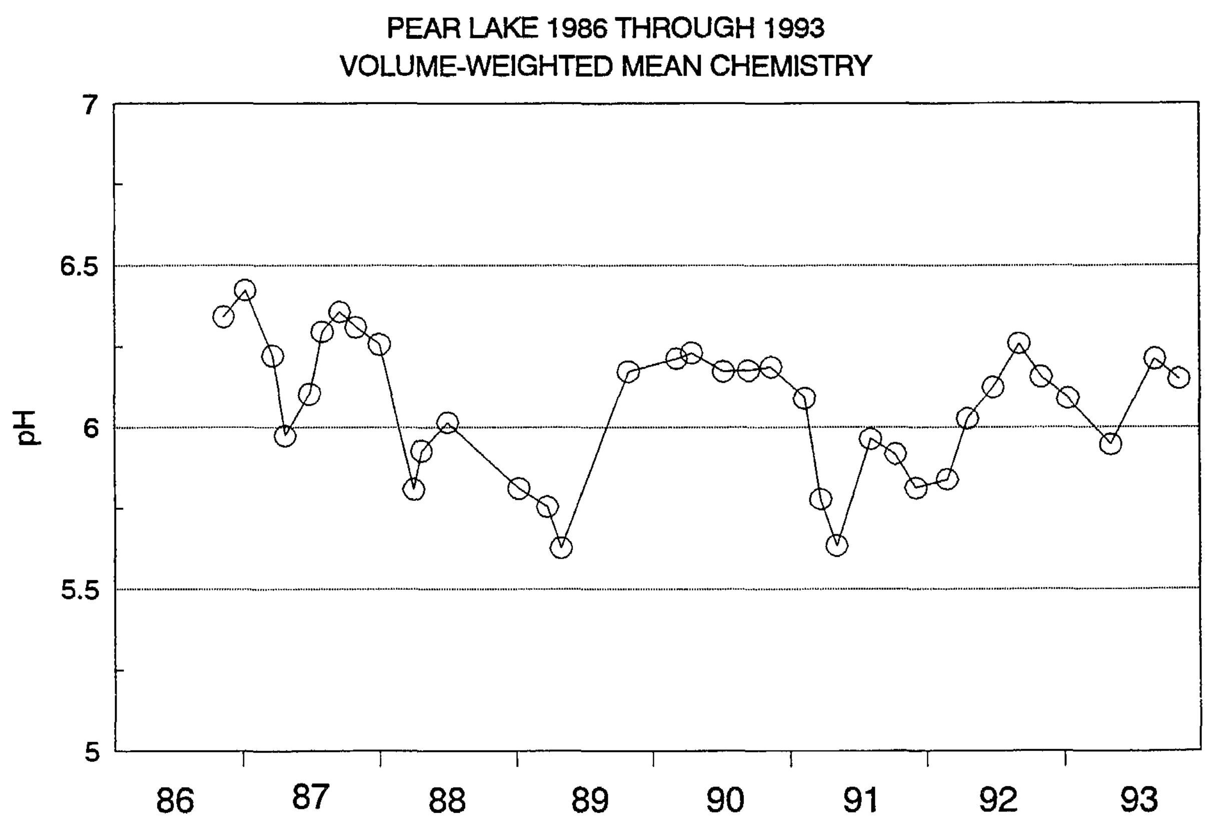
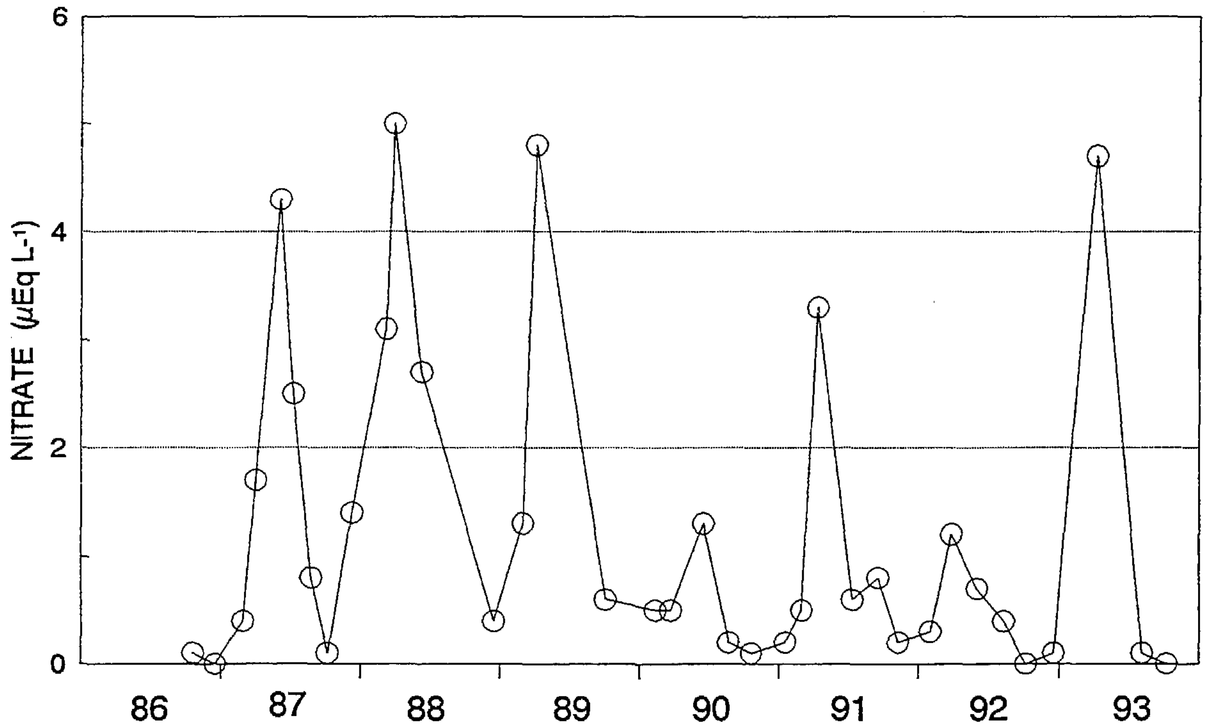

PEAR LAKE 1986 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
pH
7
6.5
6
5.5
5
86
87
88
89
90
91
92
93

Figure I-120

PEAR LAKE 1986 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY



PEAR LAKE 1986 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY

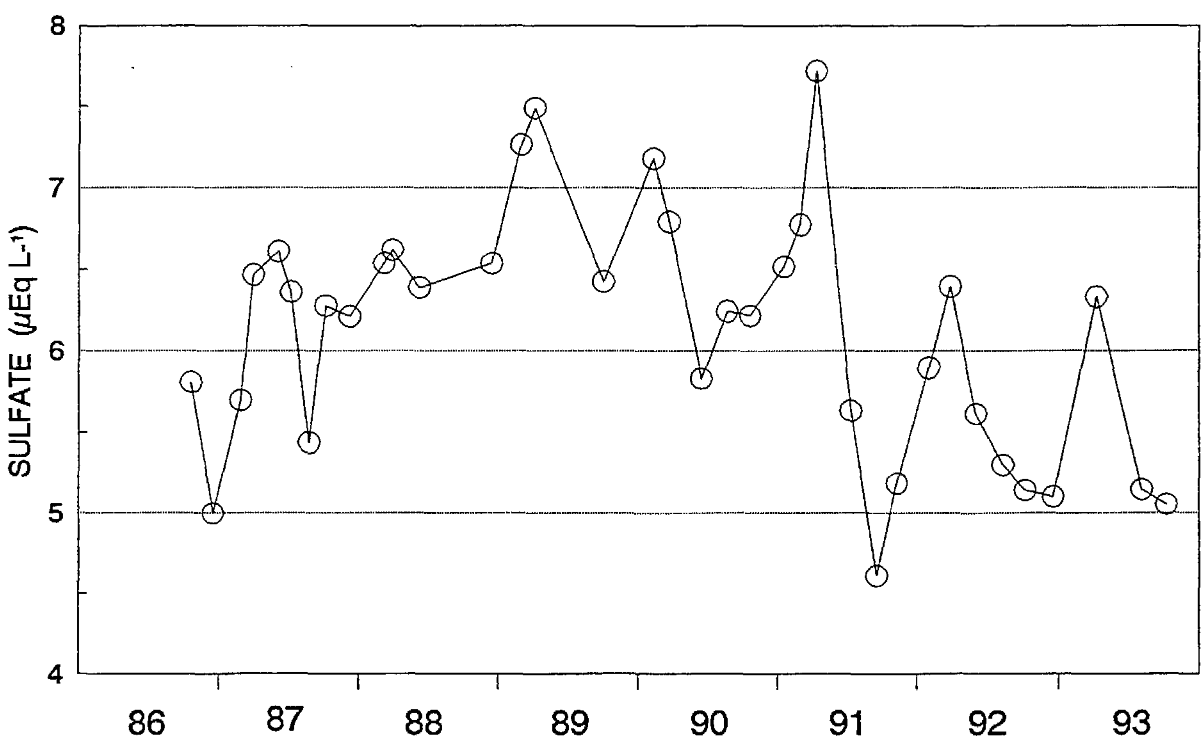
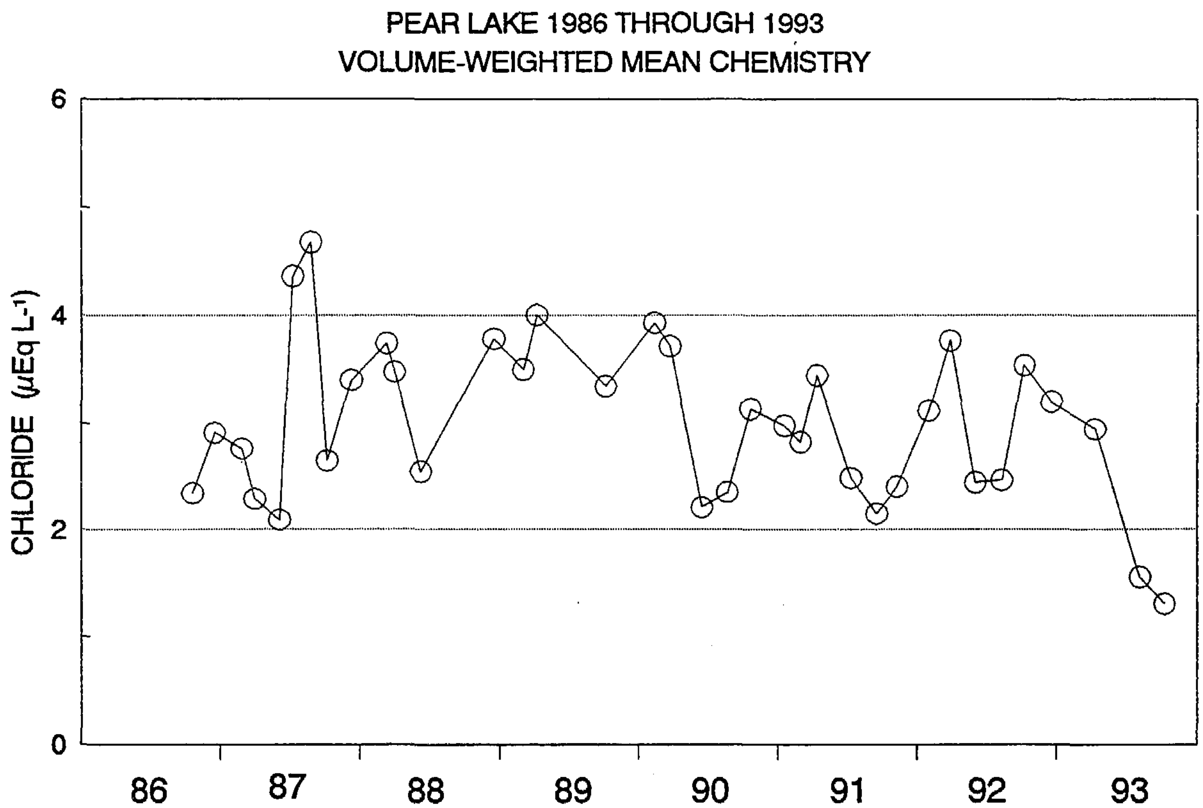


Figure I-121


PEAR LAKE 1986 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
CHLORIDE (μEq L^{-1})
0
2
4
6
86
87
88
89
90
91
92
93

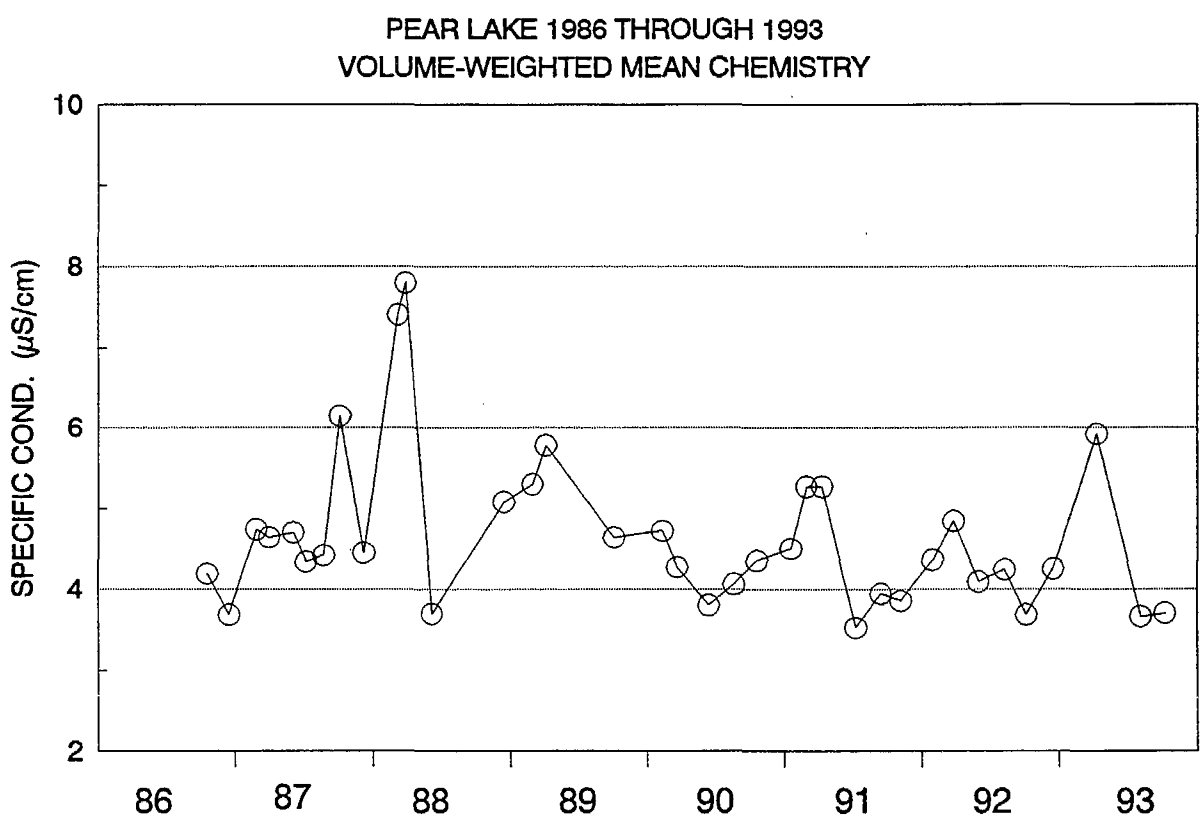
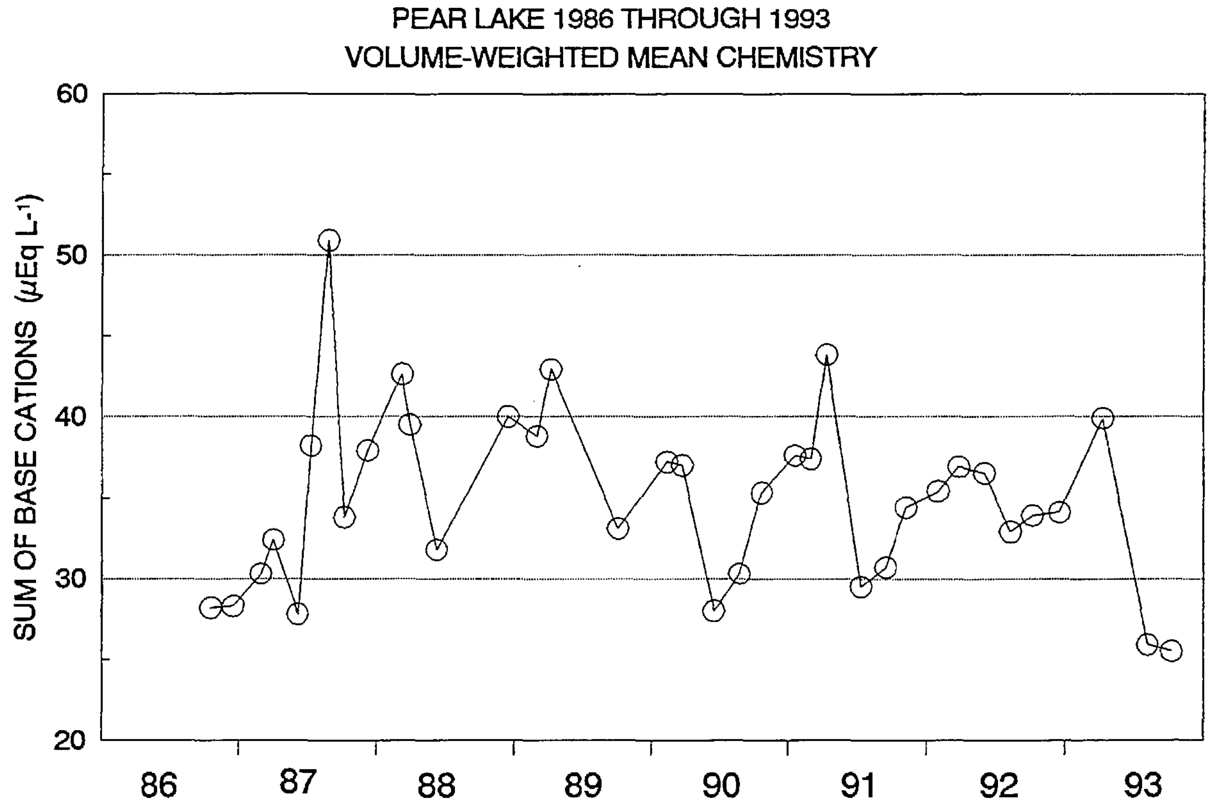

PEAR LAKE 1986 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
SPECIFIC COND. (μS/cm)
2
4
6
8
10
86
87
88
89
90
91
92
93

Figure I-122


PEAR LAKE 1986 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
SUM OF BASE CATIONS (μEq L^{-1})
60
50
40
30
20
86
87
88
89
90
91
92
93

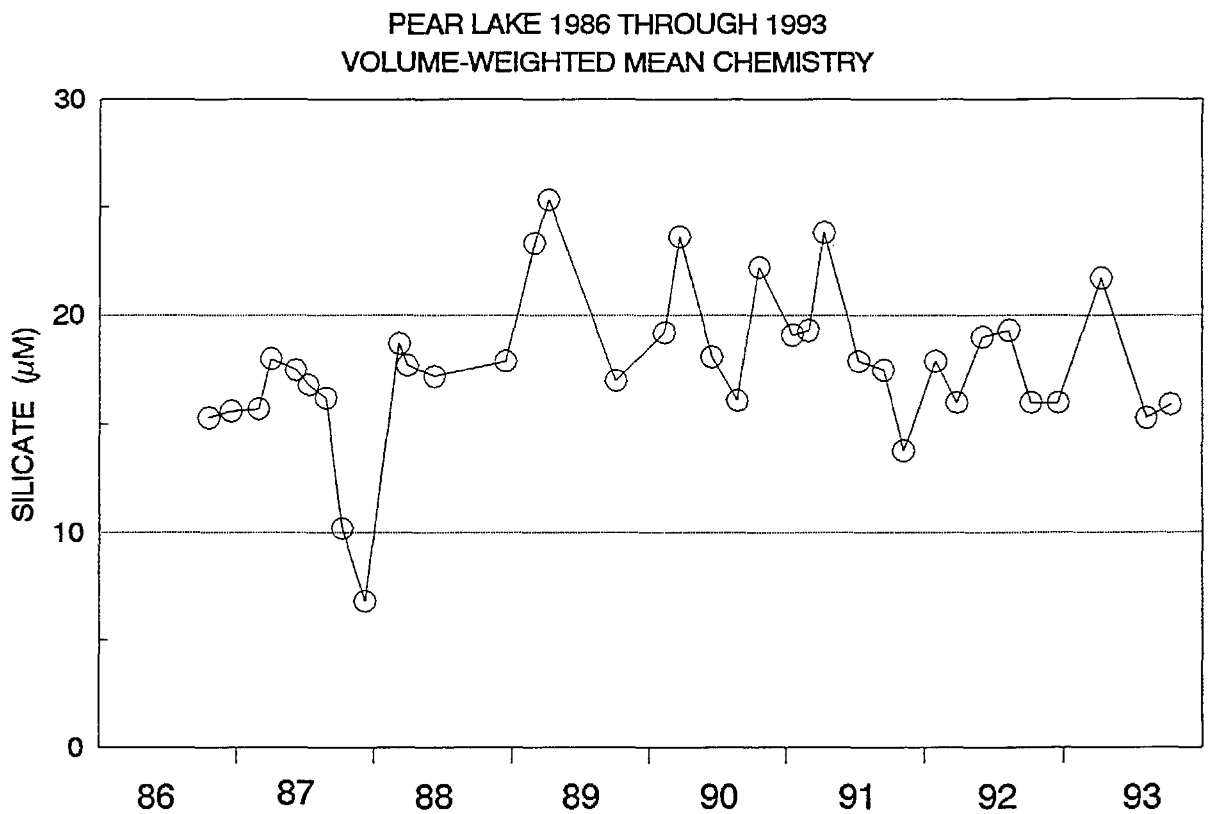
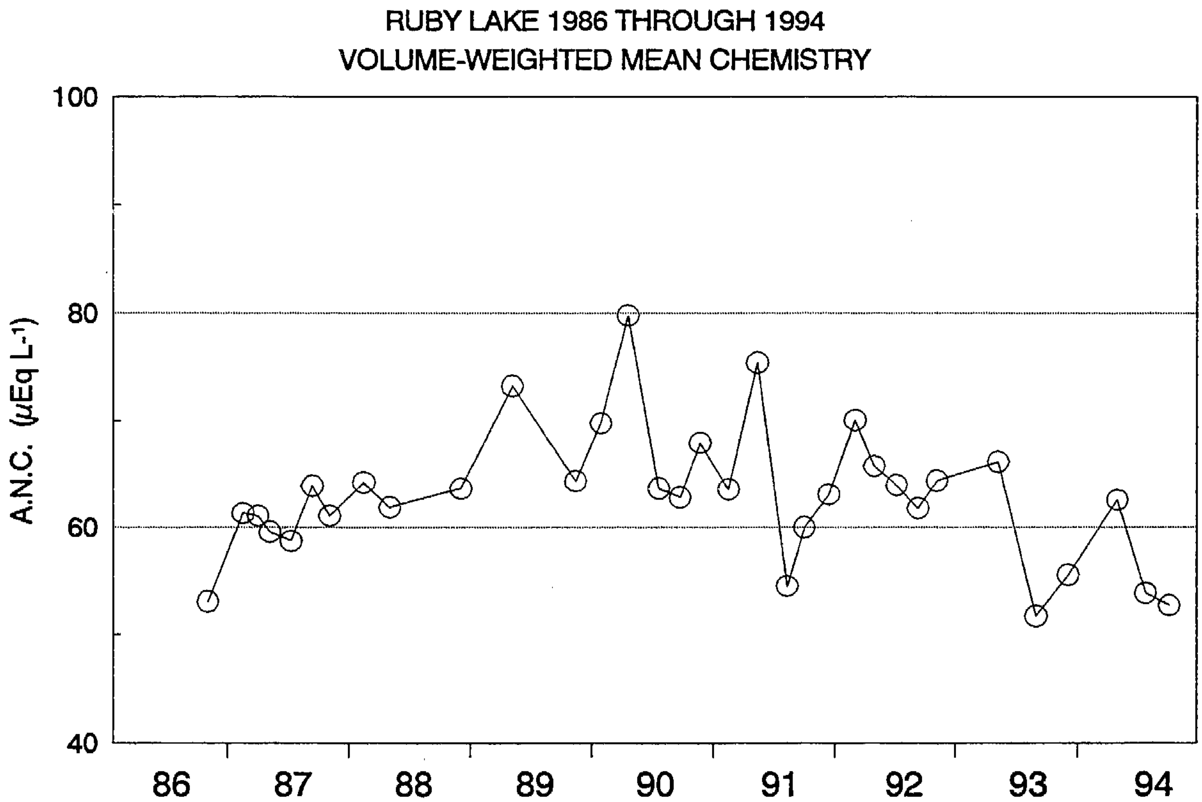

PEAR LAKE 1986 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
SILICATE (μM)
30
20
10
0
86
87
88
89
90
91
92
93

Figure I-123


RUBY LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
A.N.C. (μEq L-1)
100
80
60
40
86
87
88
89
90
91
92
93
94

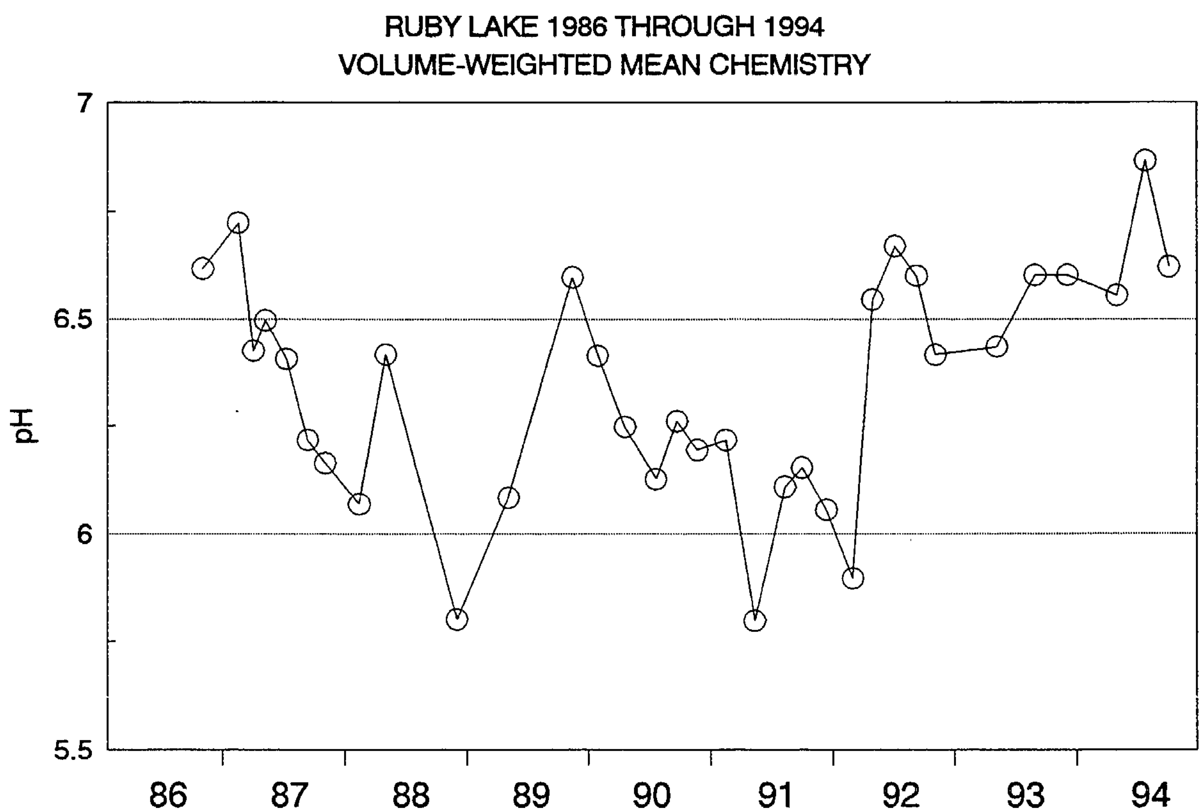
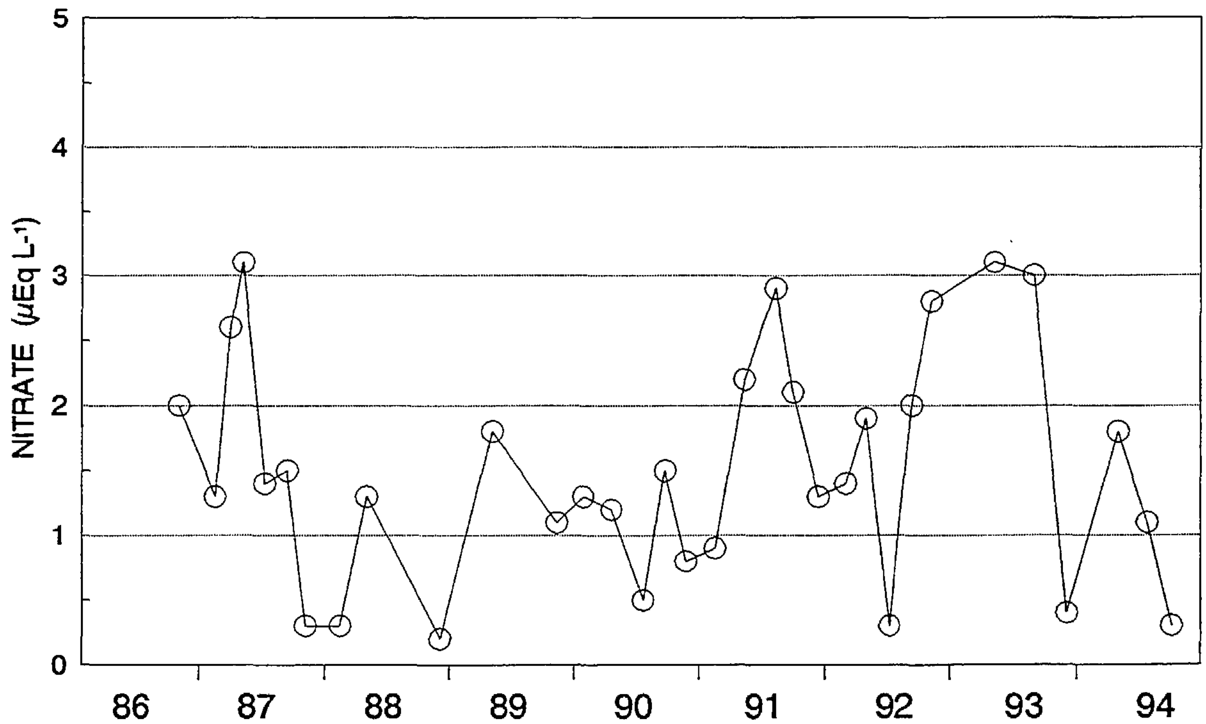

RUBY LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
pH
7
6.5
6
5.5
86
87
88
89
90
91
92
93
94

Figure I-124

RUBY LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY



RUBY LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY

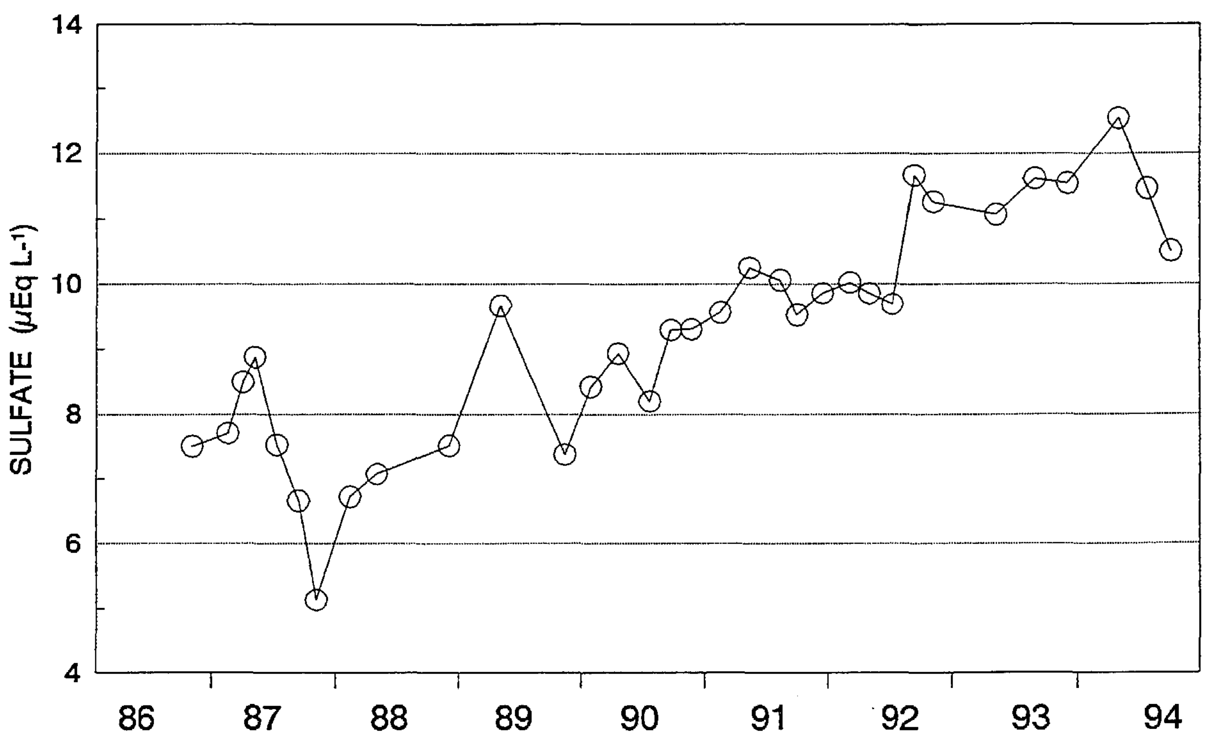
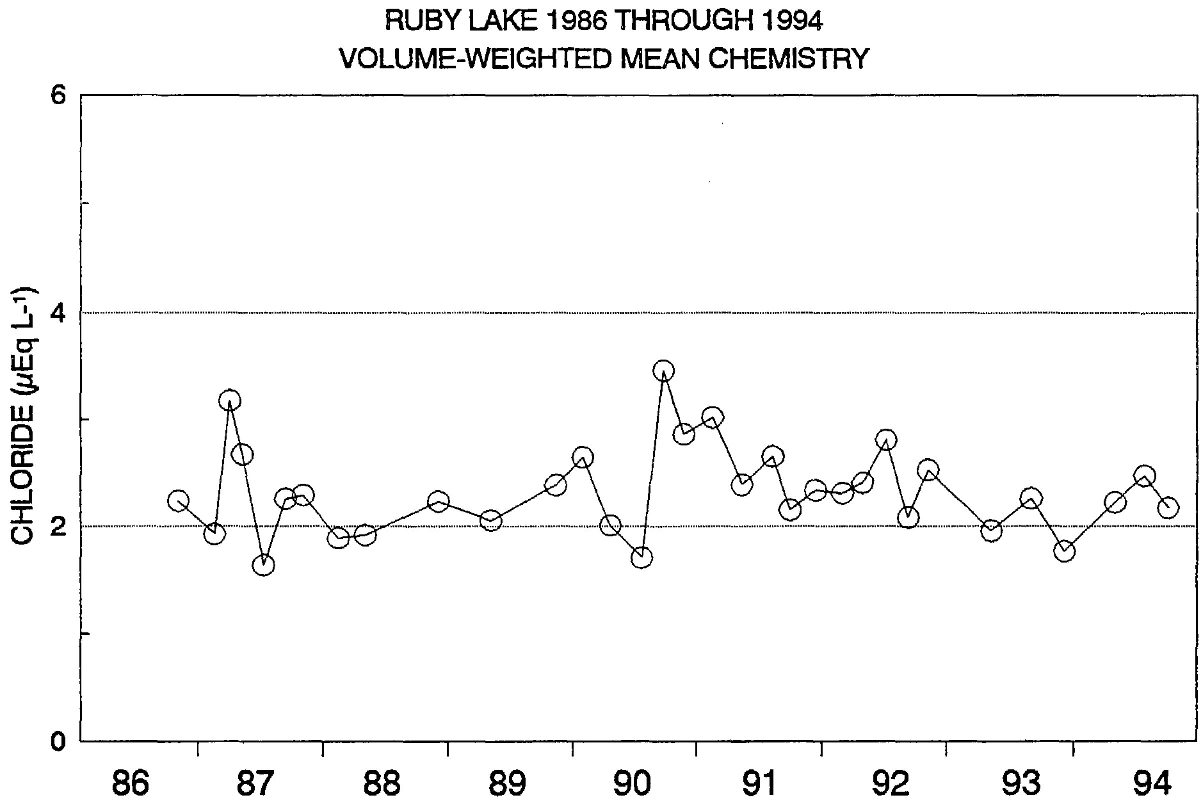


Figure I-125


RUBY LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
CHLORIDE (μEq L-1)
0
2
4
6
86
87
88
89
90
91
92
93
94

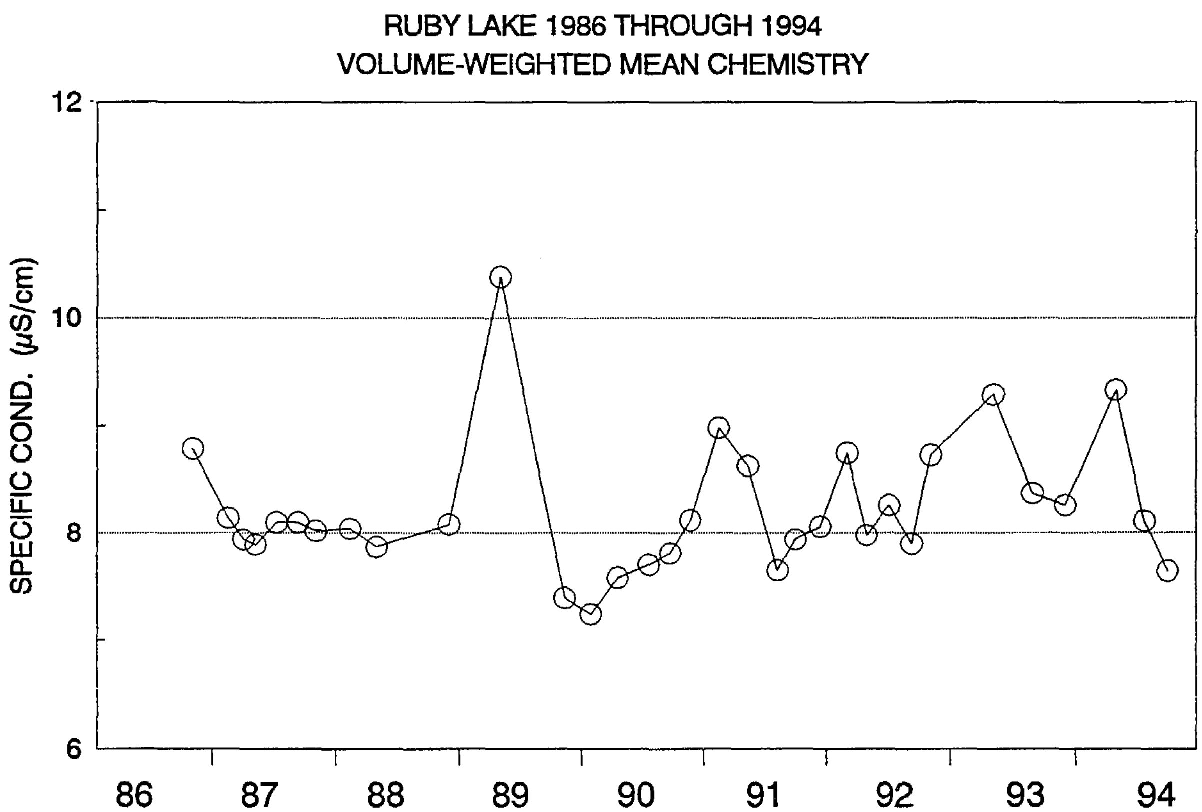
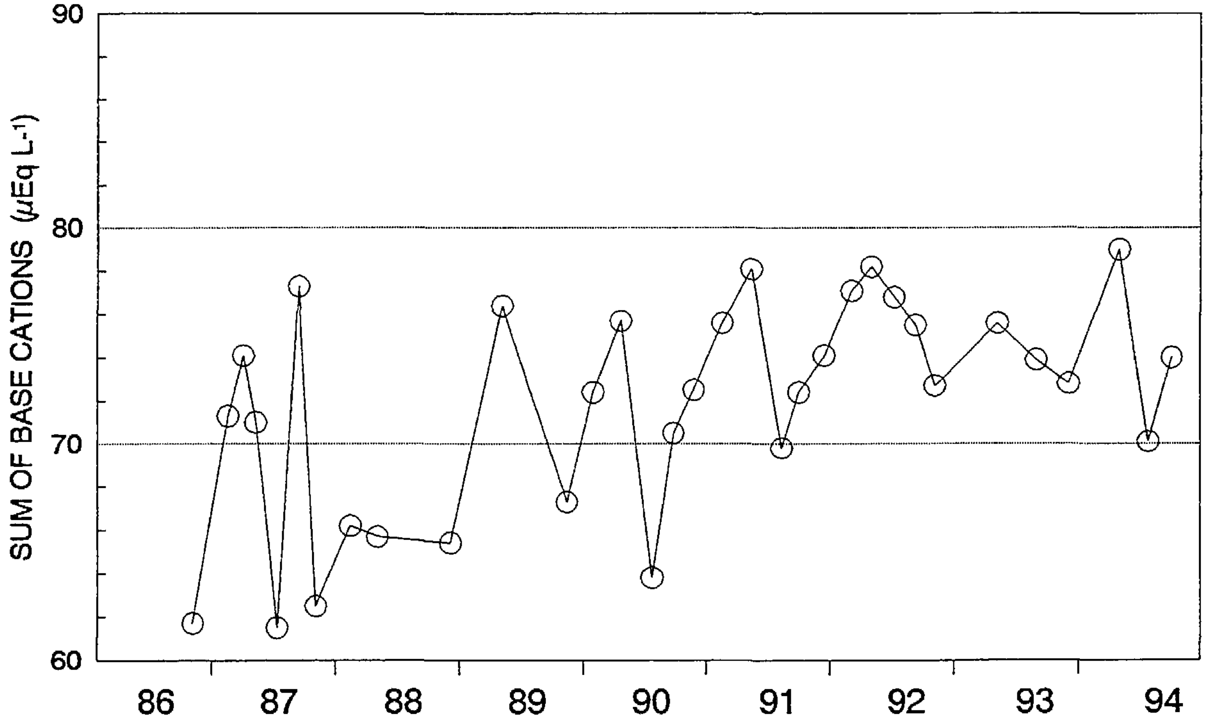

RUBY LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
SPECIFIC COND. (μS/cm)
6
8
10
12
86
87
88
89
90
91
92
93
94

Figure I-126

RUBY LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY



RUBY LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY

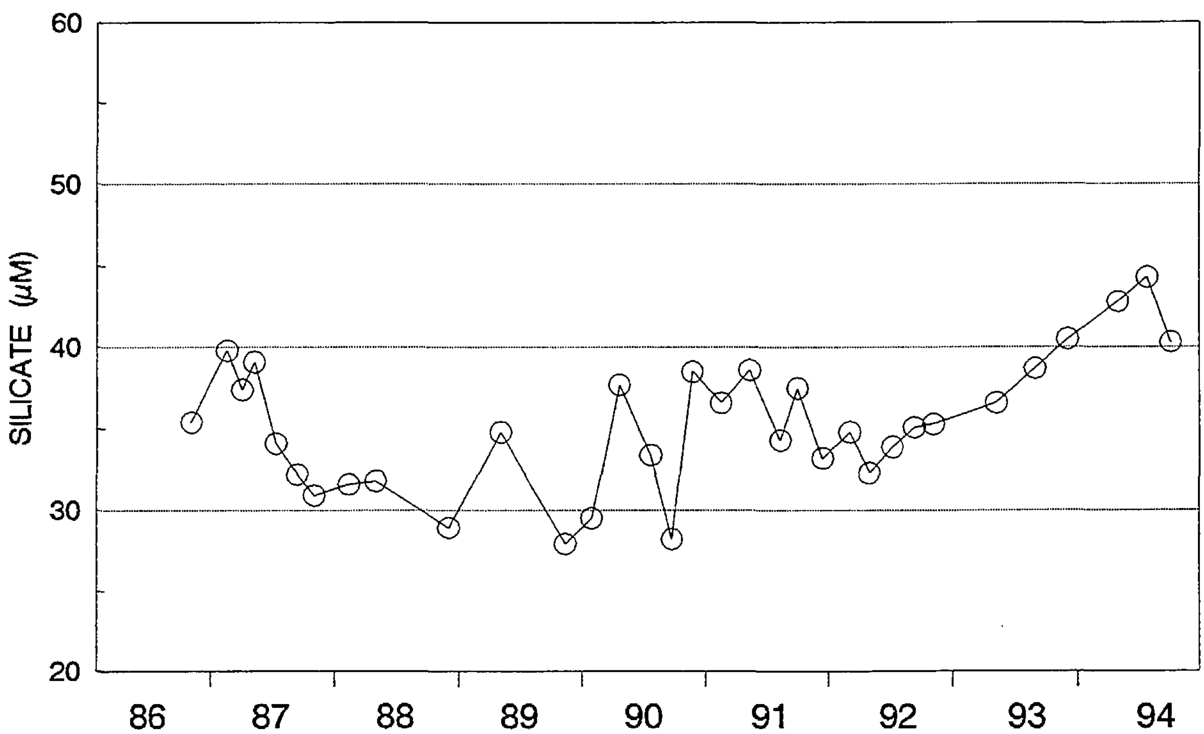
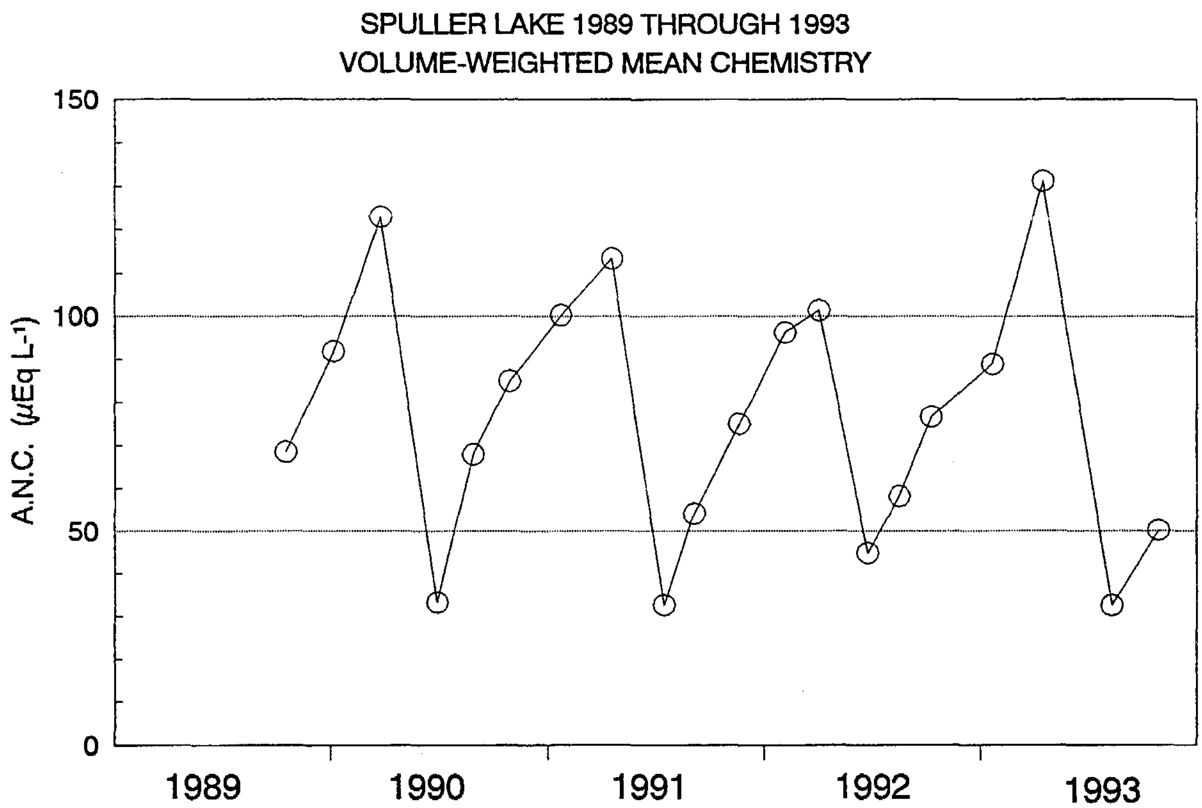


Figure I-127


SPULLER LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
A.N.C. (μEq L-1)
150
100
50
0
1989
1990
1991
1992
1993

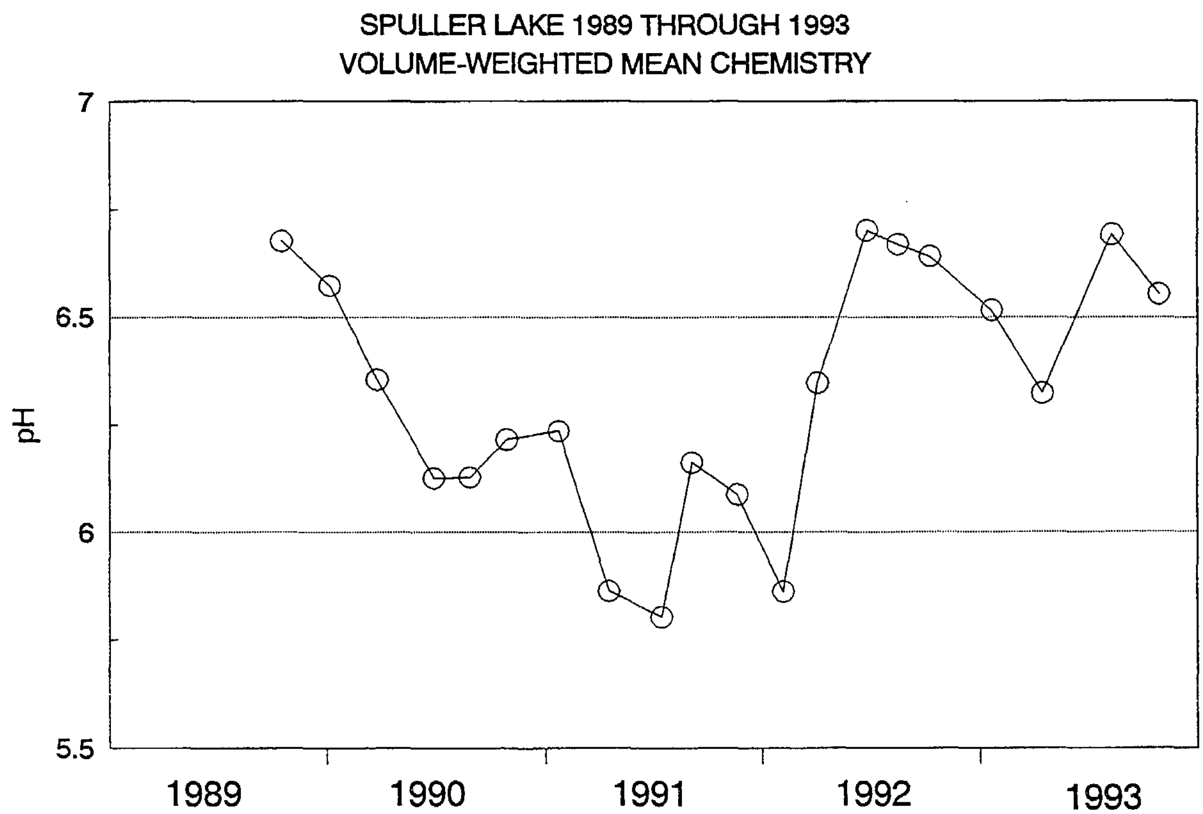

SPULLER LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
pH
7
6.5
6
5.5
1989
1990
1991
1992
1993

Figure I-128

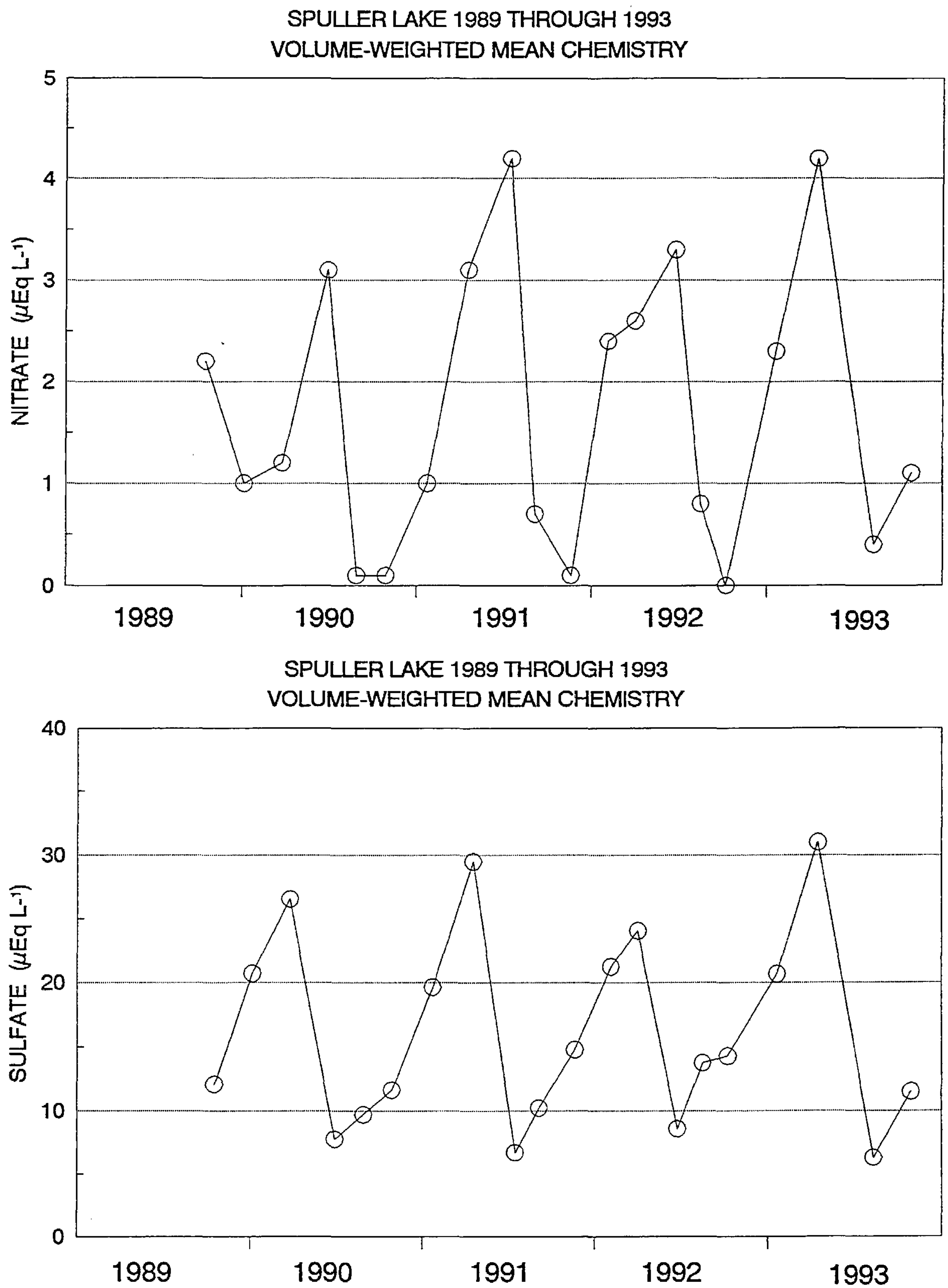
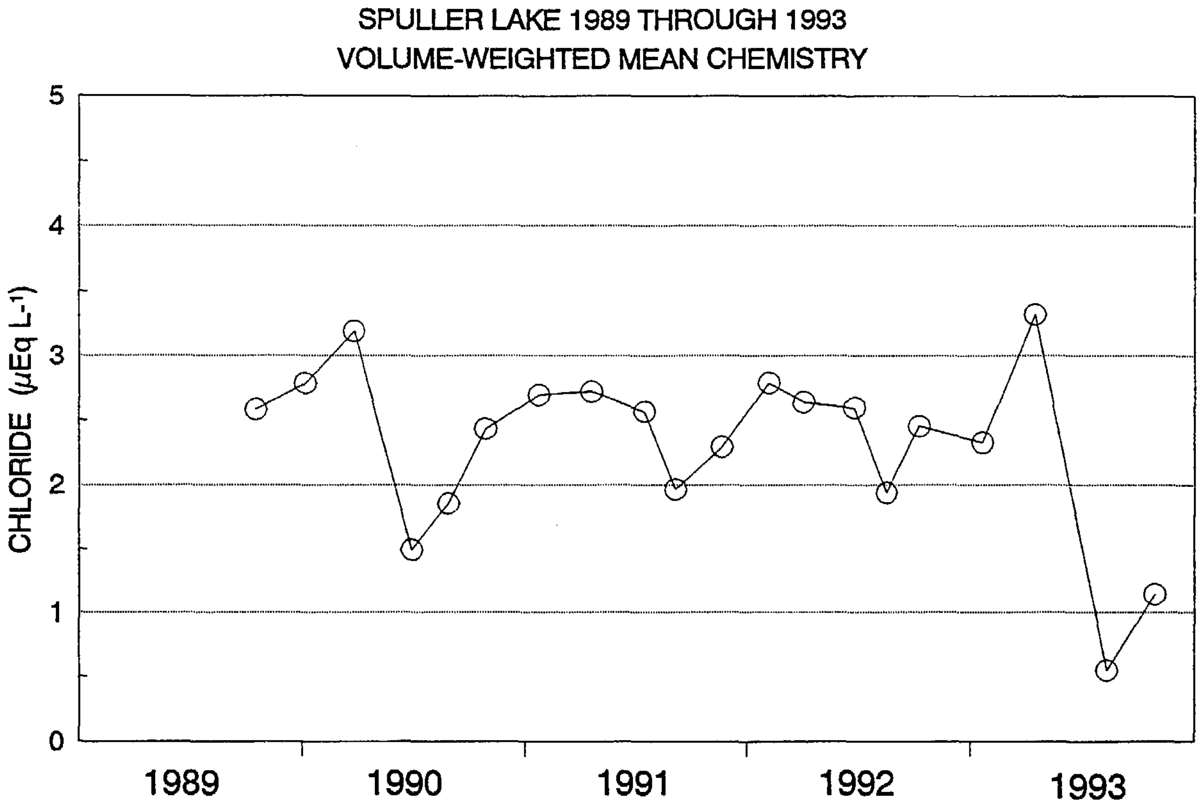

SPULLER LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
NITRATE (μEq L-1)
0
1
2
3
4
5
1989
1990
1991
1992
1993
SPULLER LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
SULFATE (μEq L-1)
0
10
20
30
40
1989
1990
1991
1992
1993

Figure I-129


SPULLER LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
CHLORIDE (µEq L-1)
0
1
2
3
4
5
1989
1990
1991
1992
1993

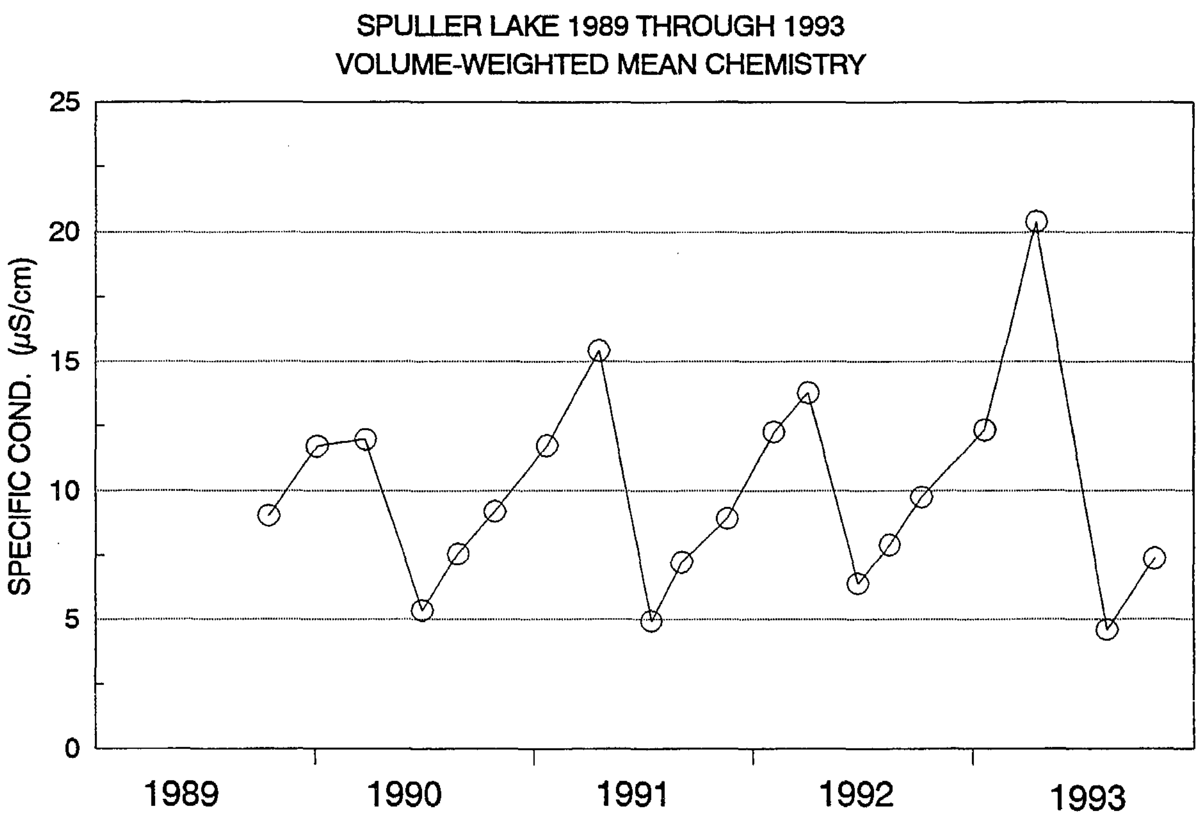
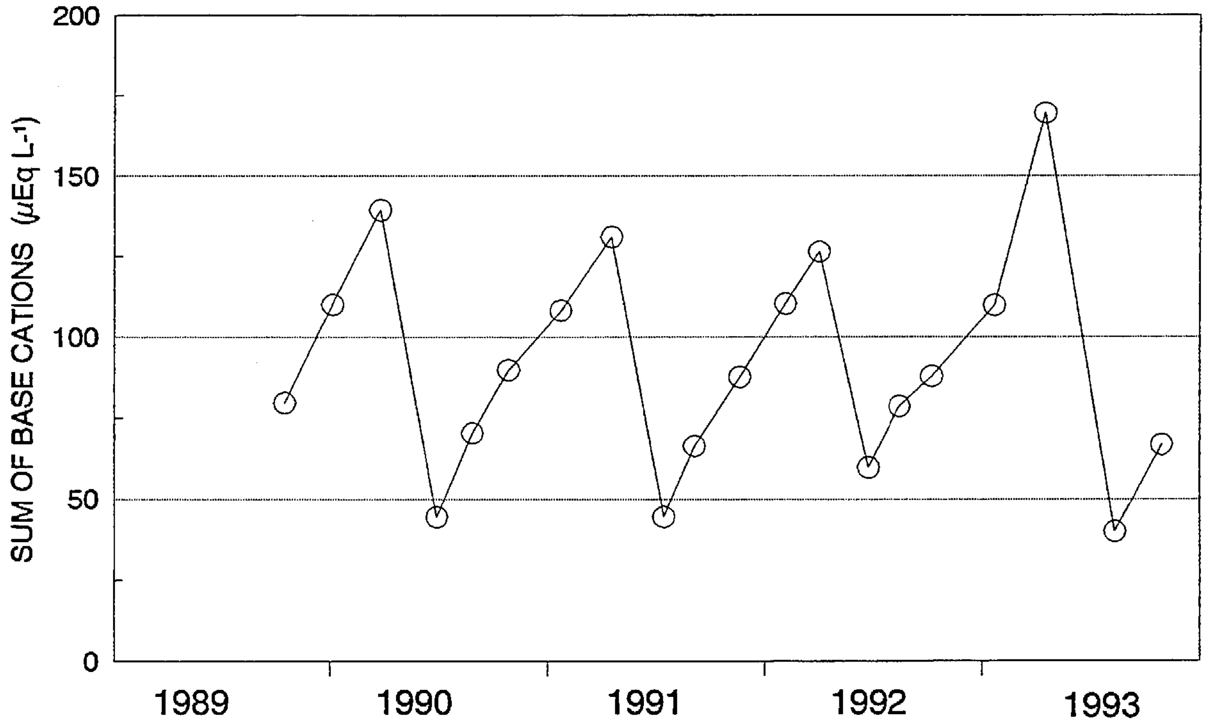

SPULLER LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY
SPECIFIC COND. (µS/cm)
0
5
10
15
20
25
1989
1990
1991
1992
1993

Figure I-130

SPULLER LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY



SPULLER LAKE 1989 THROUGH 1993
VOLUME-WEIGHTED MEAN CHEMISTRY

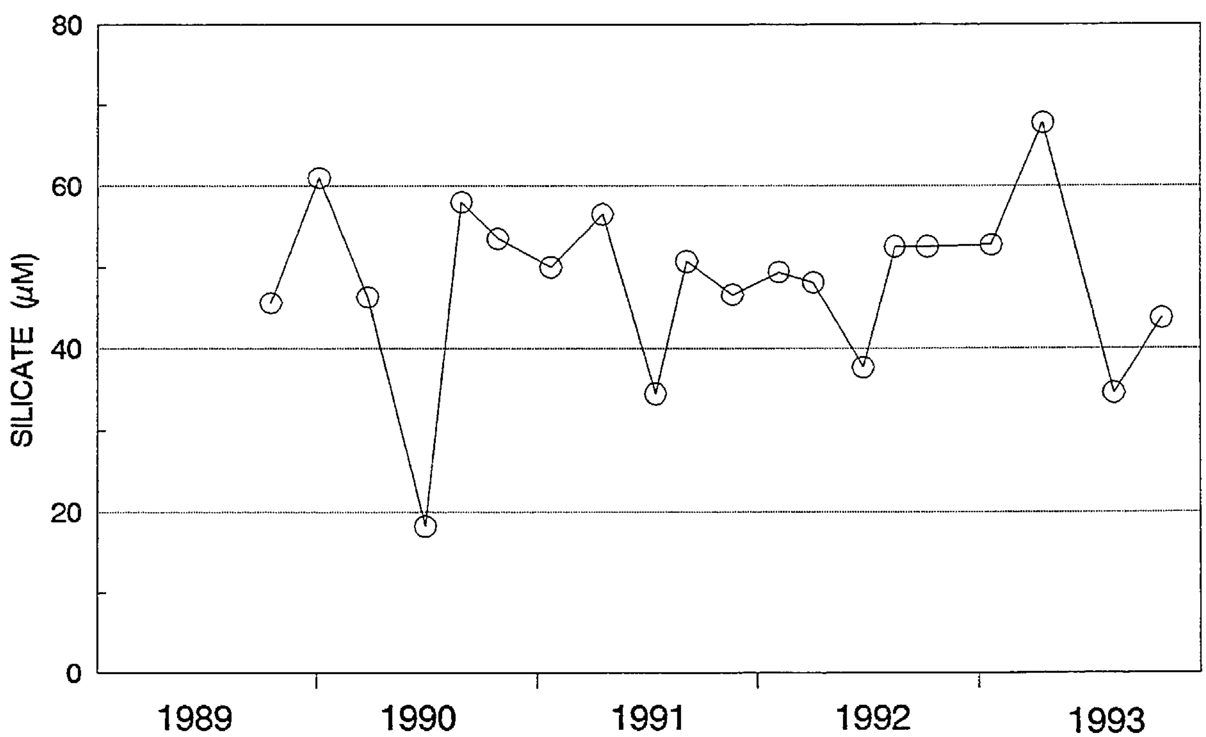
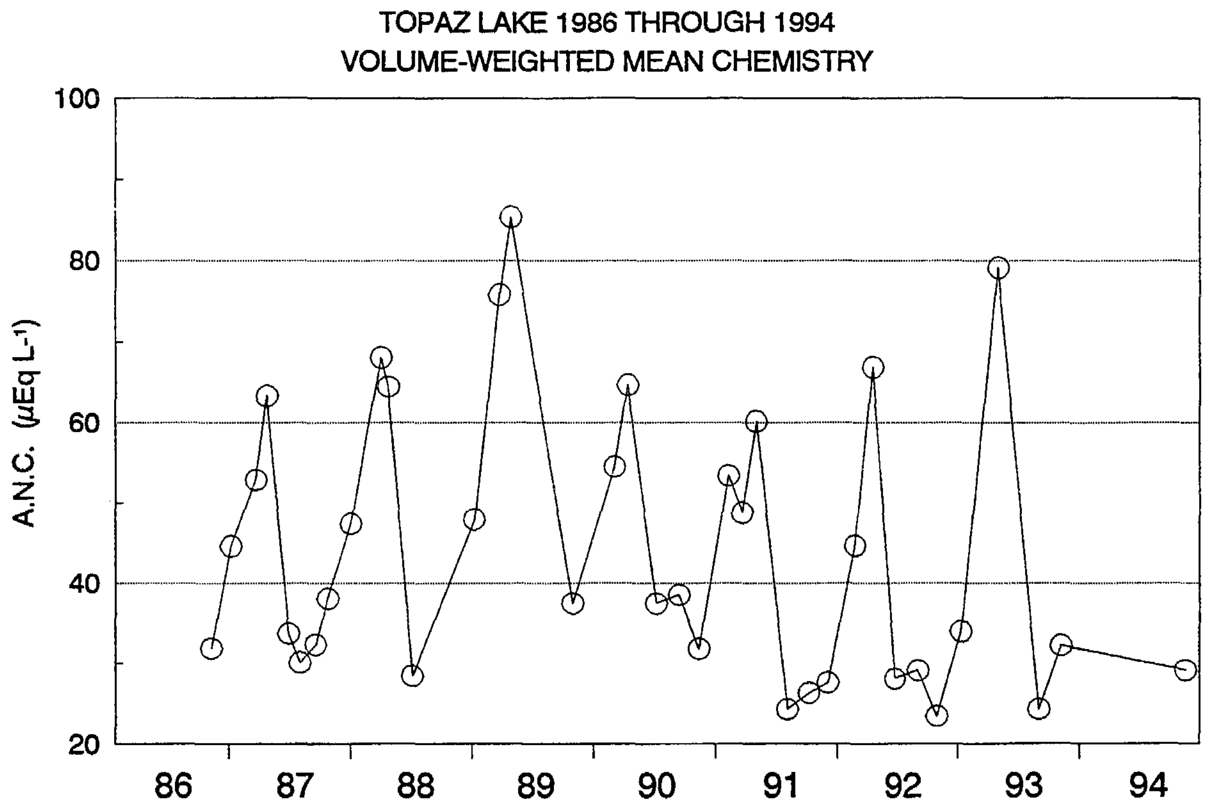


Figure I-131


TOPAZ LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
A.N.C. (µEq L⁻¹)
100
80
60
40
20
86
87
88
89
90
91
92
93
94

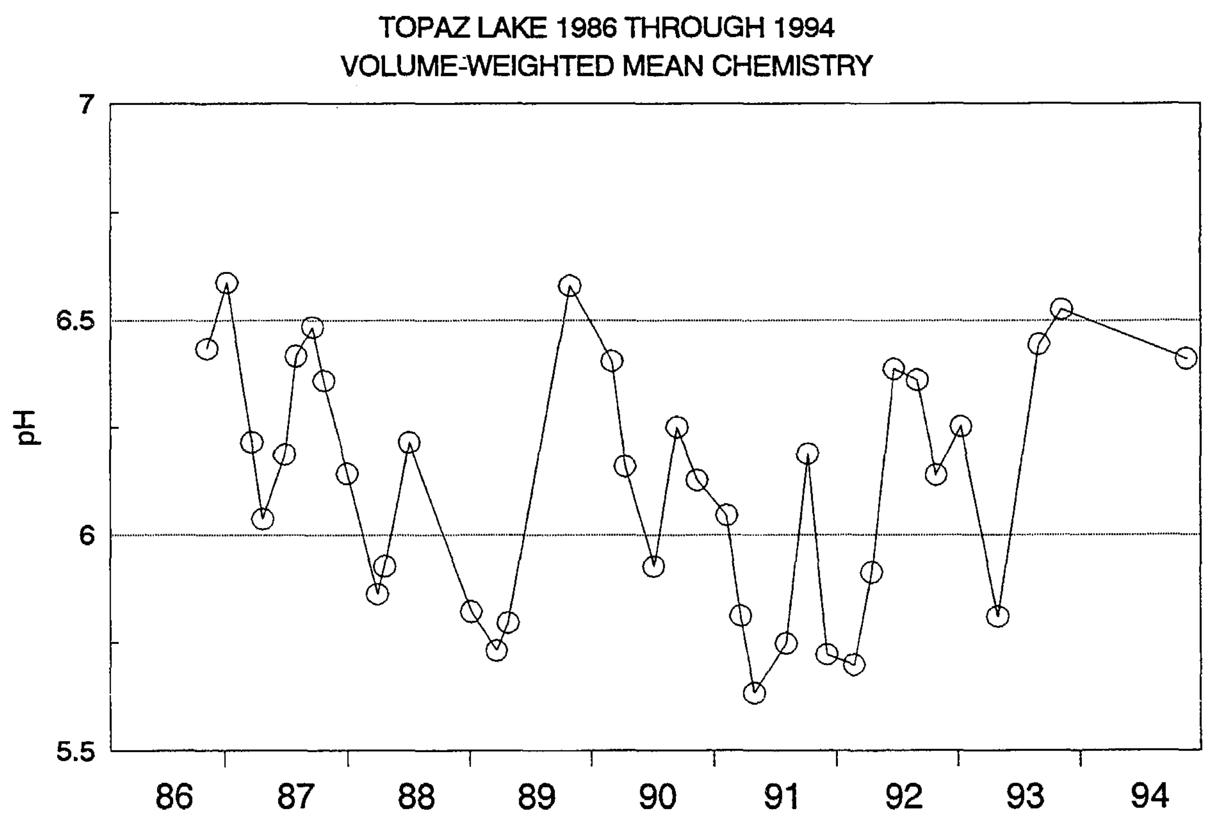
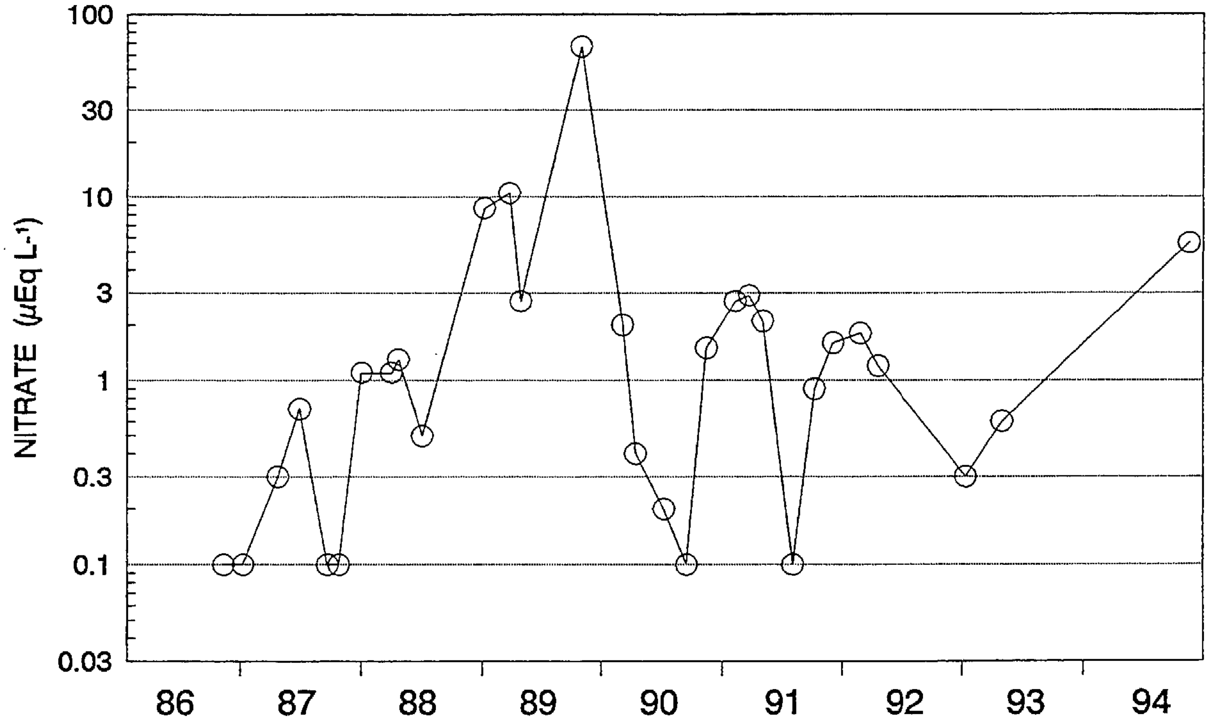

TOPAZ LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
pH
7
6.5
6
5.5
86
87
88
89
90
91
92
93
94

Figure I-132

TOPAZ LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY



TOPAZ LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY

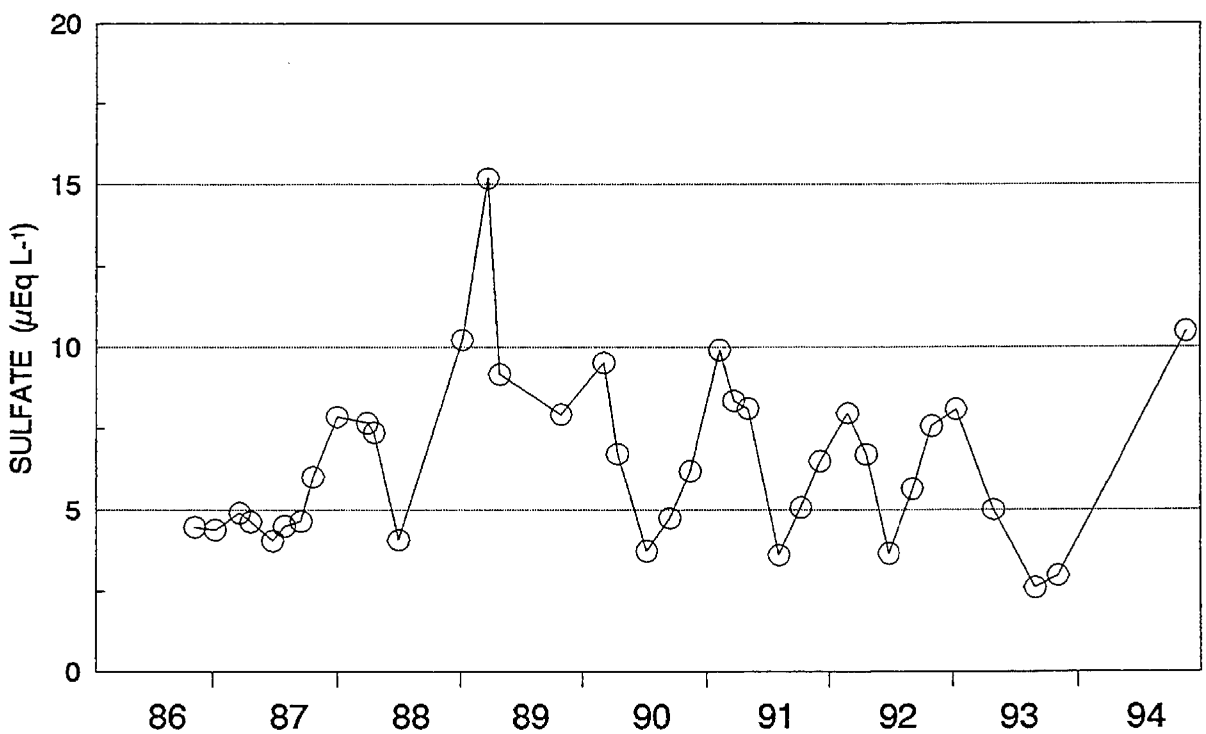
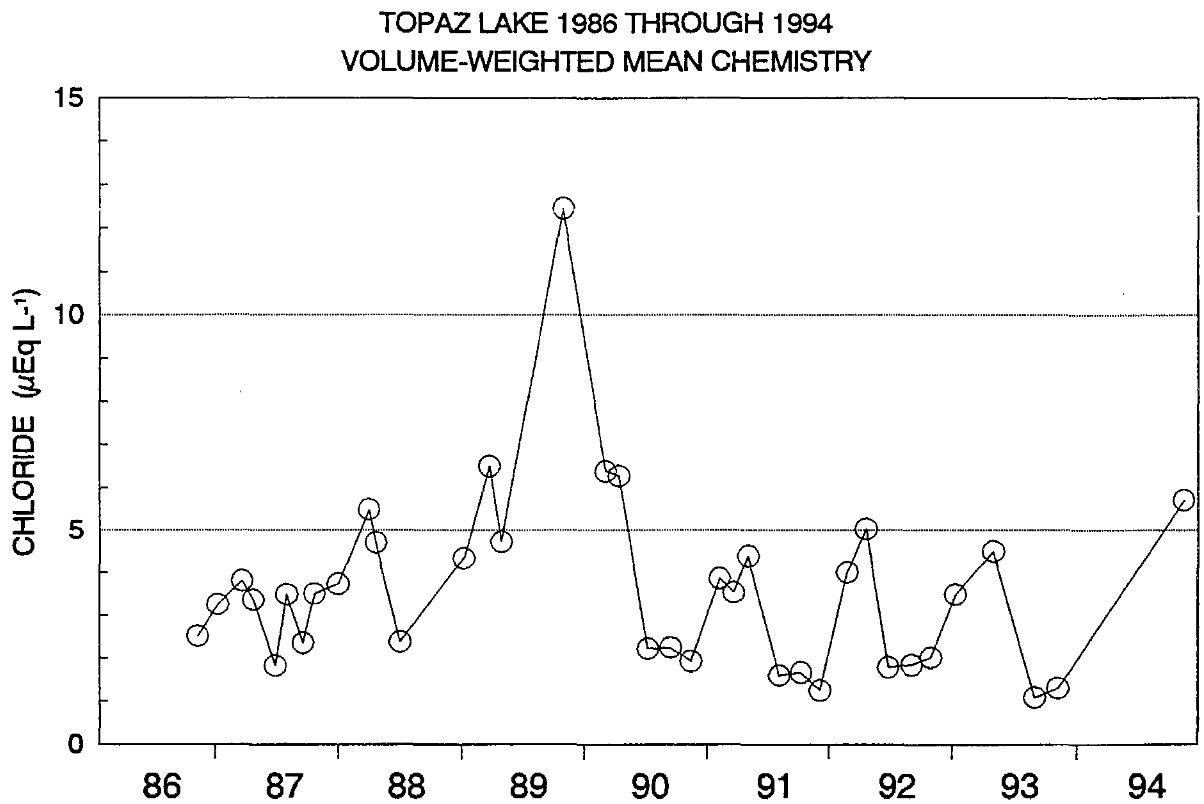


Figure I-133


TOPAZ LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
CHLORIDE (µEq L⁻¹)
15
10
5
0
86
87
88
89
90
91
92
93
94

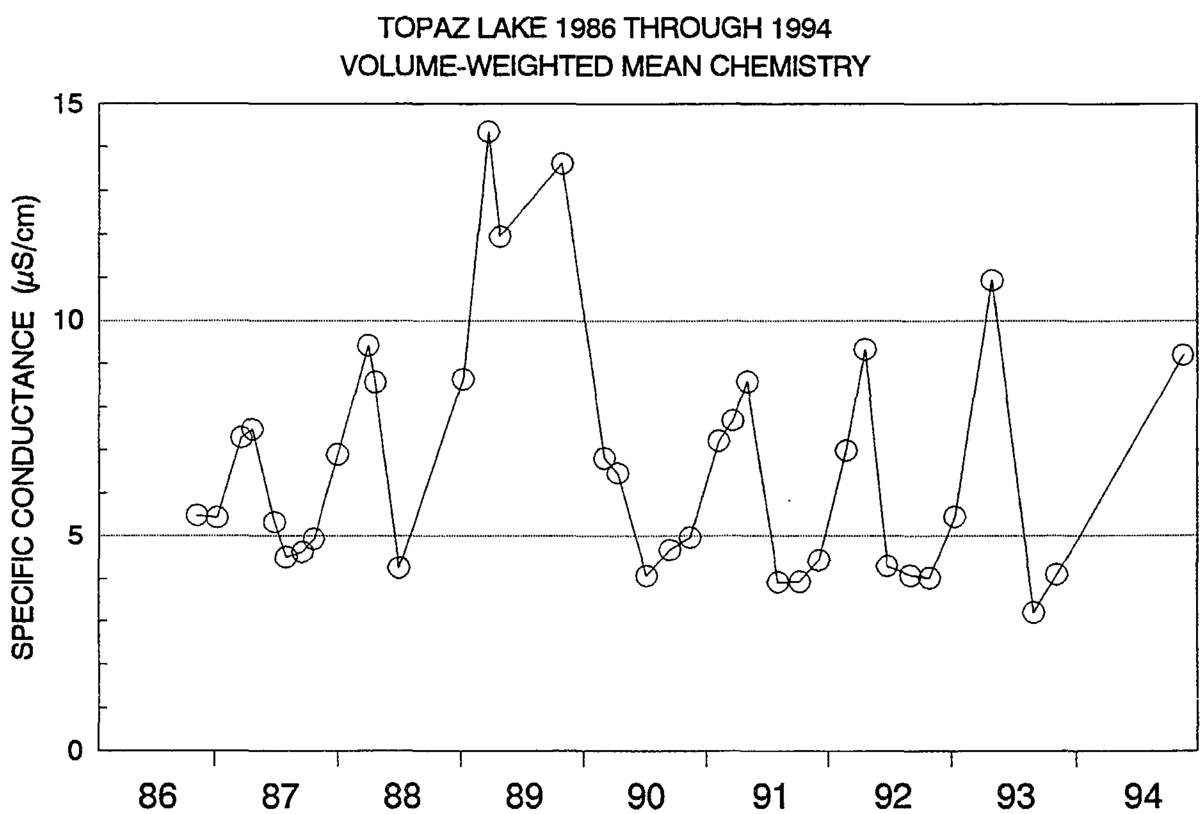
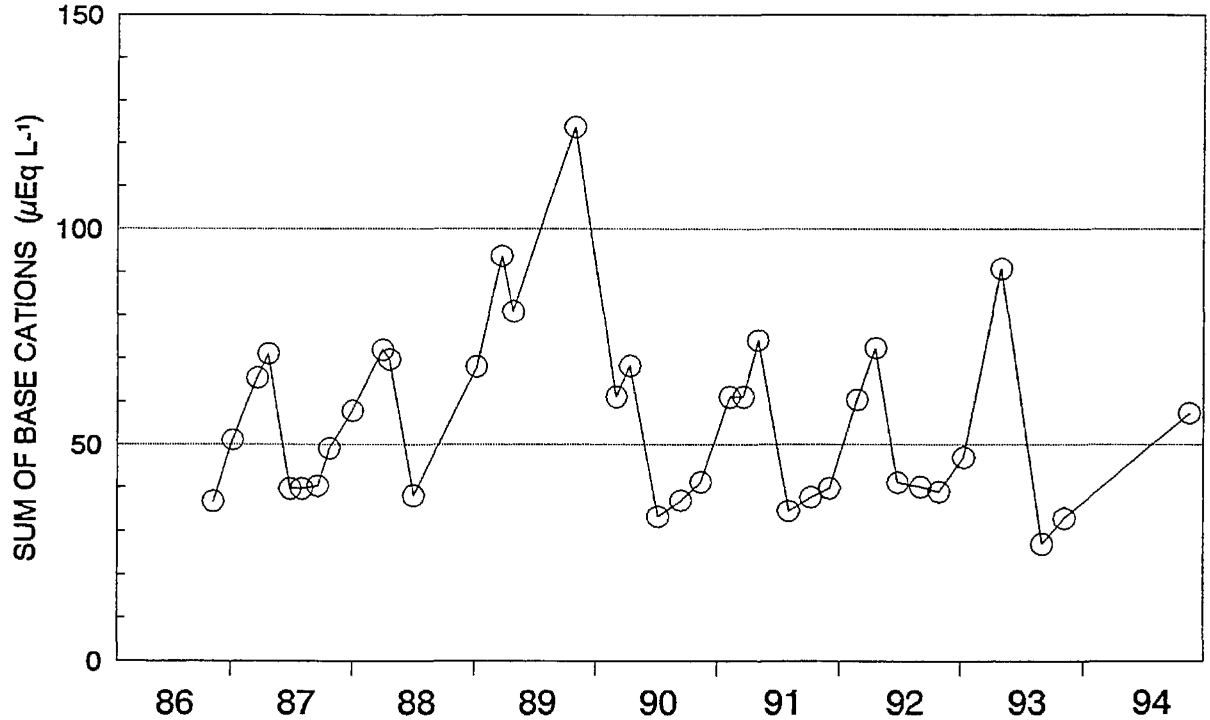

TOPAZ LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY
SPECIFIC CONDUCTANCE (µS/cm)
15
10
5
0
86
87
88
89
90
91
92
93
94

Figure I-134

TOPAZ LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY



TOPAZ LAKE 1986 THROUGH 1994
VOLUME-WEIGHTED MEAN CHEMISTRY

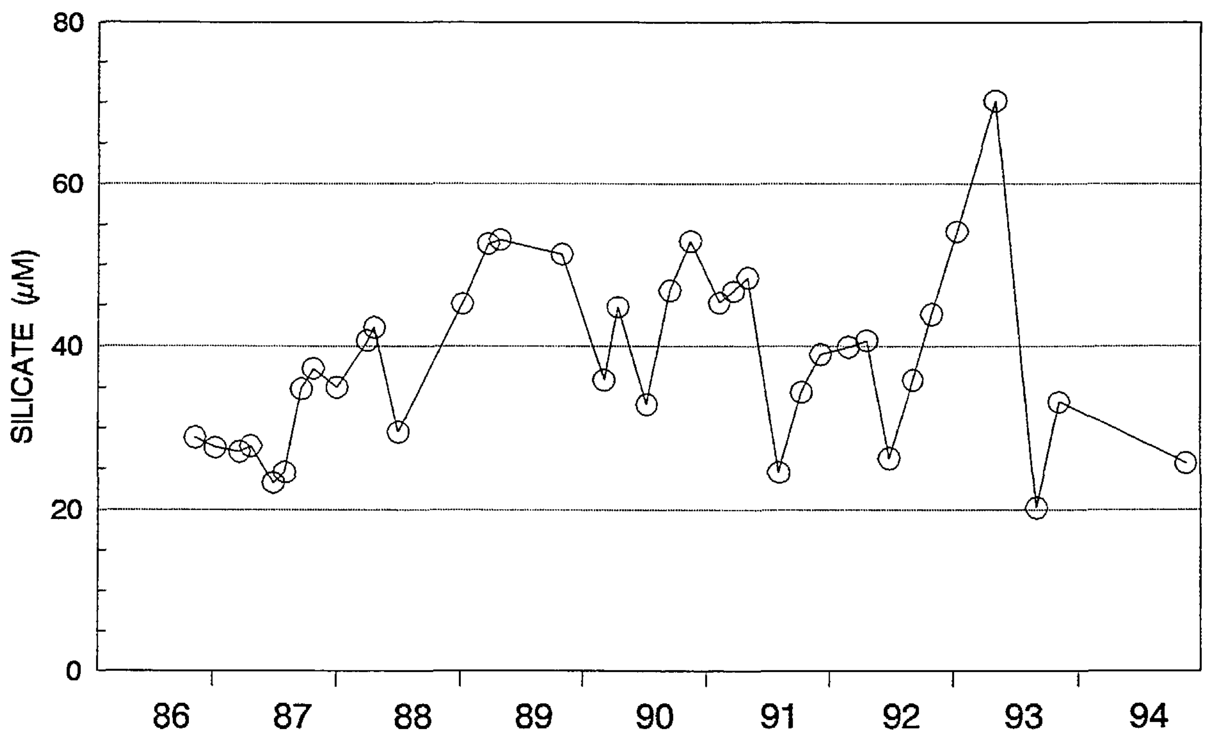


Figure I-135

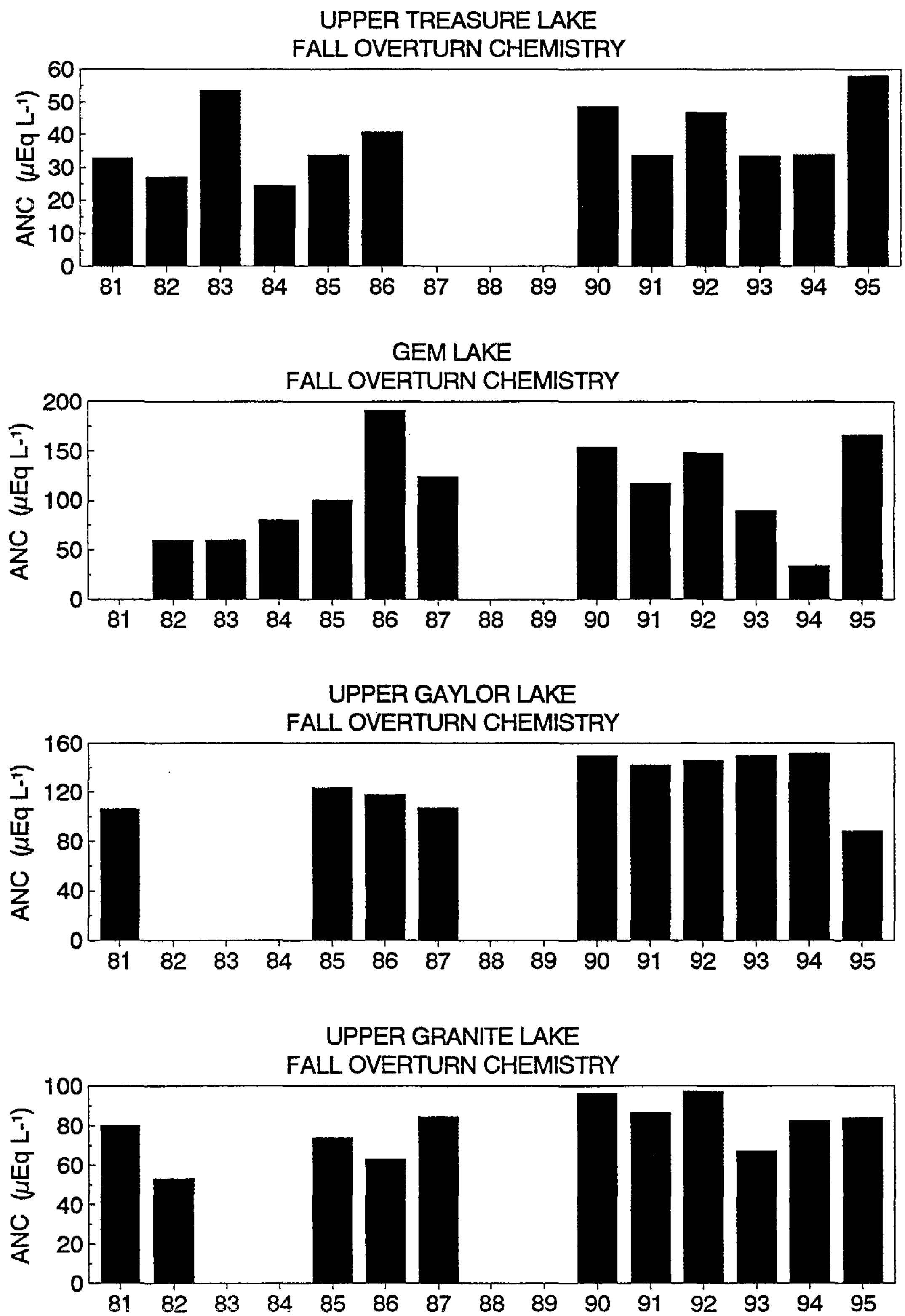

UPPER TREASURE LAKE
FALL OVERTURN CHEMISTRY
ANC (μEq L^{-1})
0 10 20 30 40 50 60
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
GEM LAKE
FALL OVERTURN CHEMISTRY
ANC (μEq L^{-1})
0 50 100 150 200
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
UPPER GAYLOR LAKE
FALL OVERTURN CHEMISTRY
ANC (μEq L^{-1})
0 40 80 120 160
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
UPPER GRANITE LAKE
FALL OVERTURN CHEMISTRY
ANC (μEq L^{-1})
0 20 40 60 80 100
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95

Figure I-136

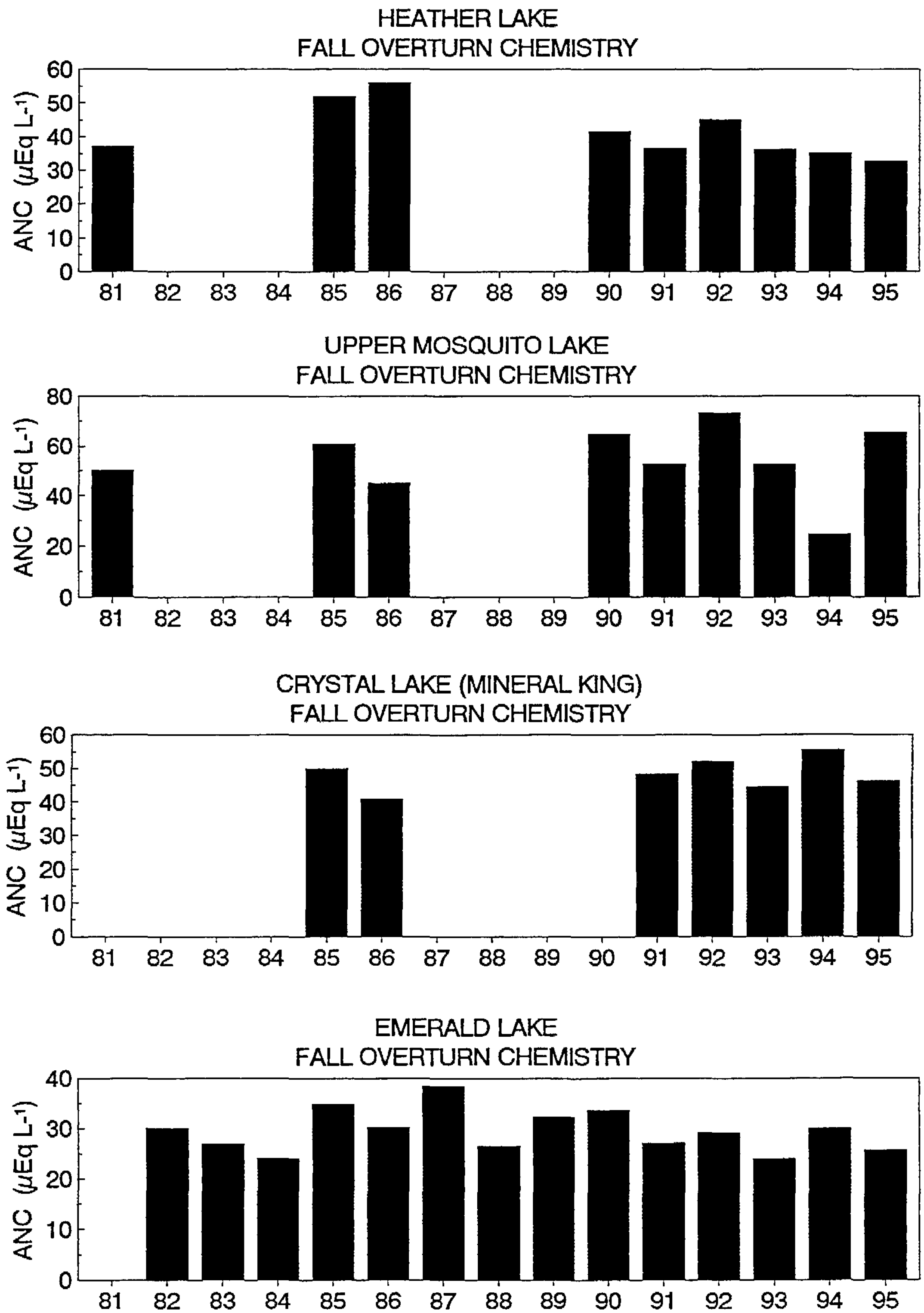

HEATHER LAKE
FALL OVERTURN CHEMISTRY
ANC (μEq L-1)
0
10
20
30
40
50
60
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
UPPER MOSQUITO LAKE
FALL OVERTURN CHEMISTRY
ANC (μEq L-1)
0
20
40
60
80
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
CRYSTAL LAKE (MINERAL KING)
FALL OVERTURN CHEMISTRY
ANC (μEq L-1)
0
10
20
30
40
50
60
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
EMERALD LAKE
FALL OVERTURN CHEMISTRY
ANC (μEq L-1)
0
10
20
30
40
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95

Figure I-137

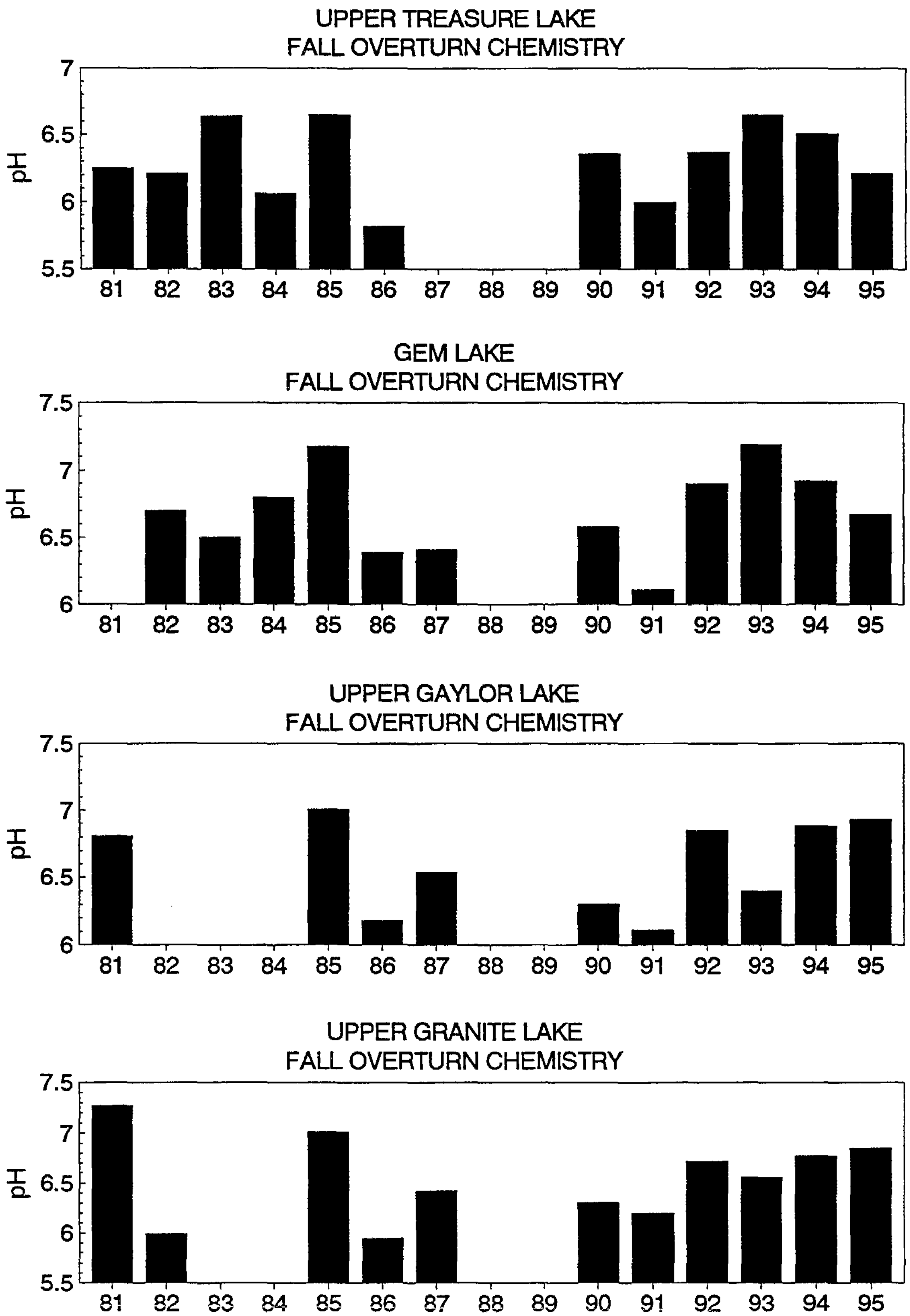

UPPER TREASURE LAKE
FALL OVERTURN CHEMISTRY
pH
7
6.5
6
5.5
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
GEM LAKE
FALL OVERTURN CHEMISTRY
pH
7.5
7
6.5
6
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
UPPER GAYLOR LAKE
FALL OVERTURN CHEMISTRY
pH
7.5
7
6.5
6
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
UPPER GRANITE LAKE
FALL OVERTURN CHEMISTRY
pH
7.5
7
6.5
6
5.5
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95

Figure I-138

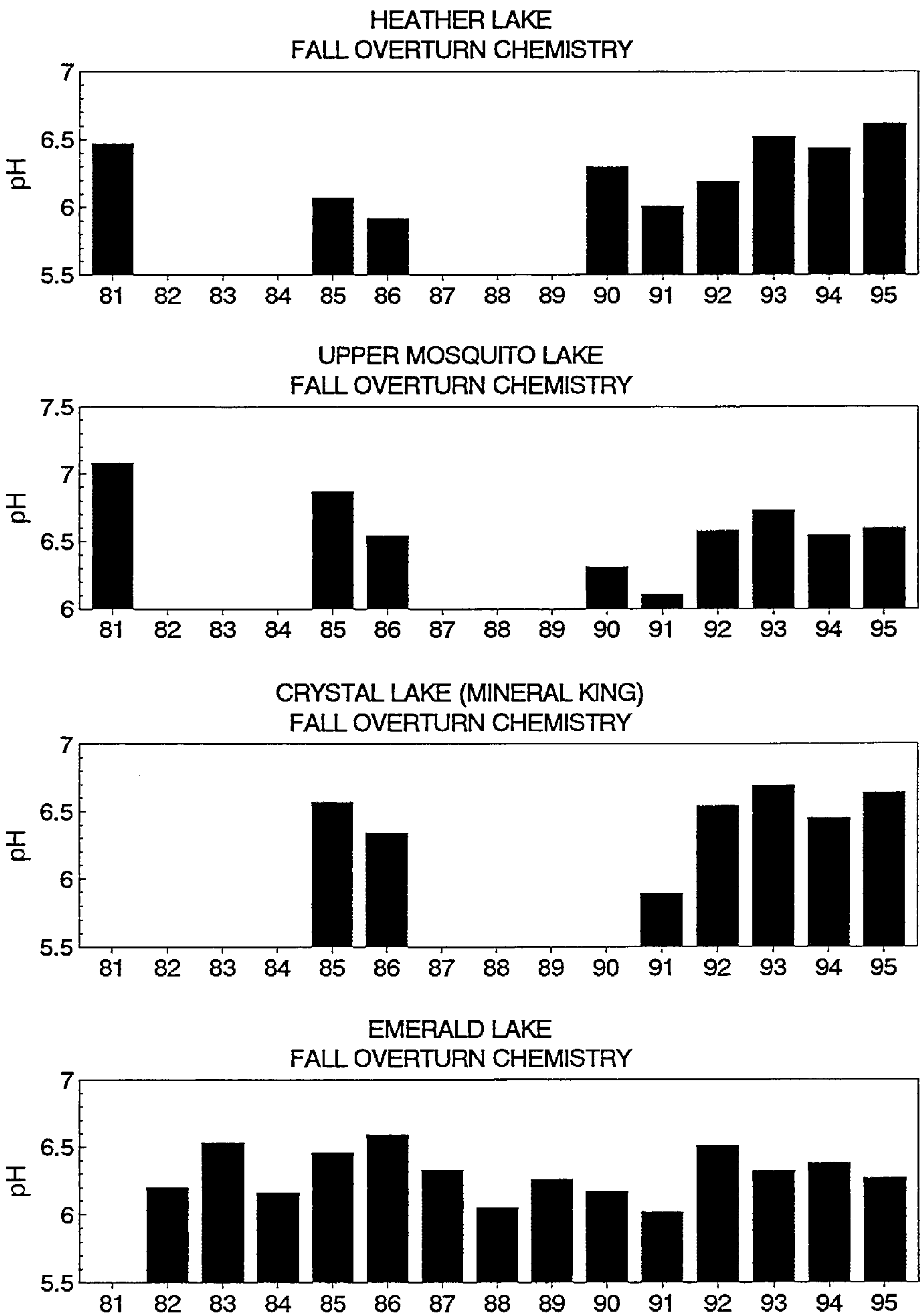
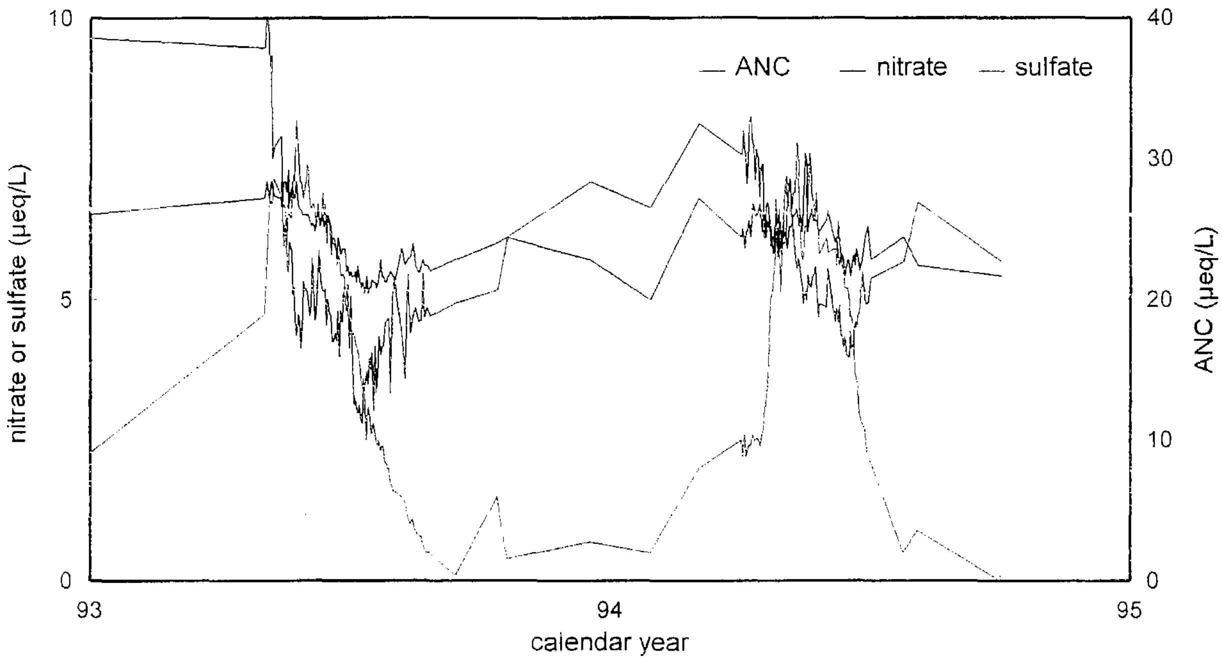
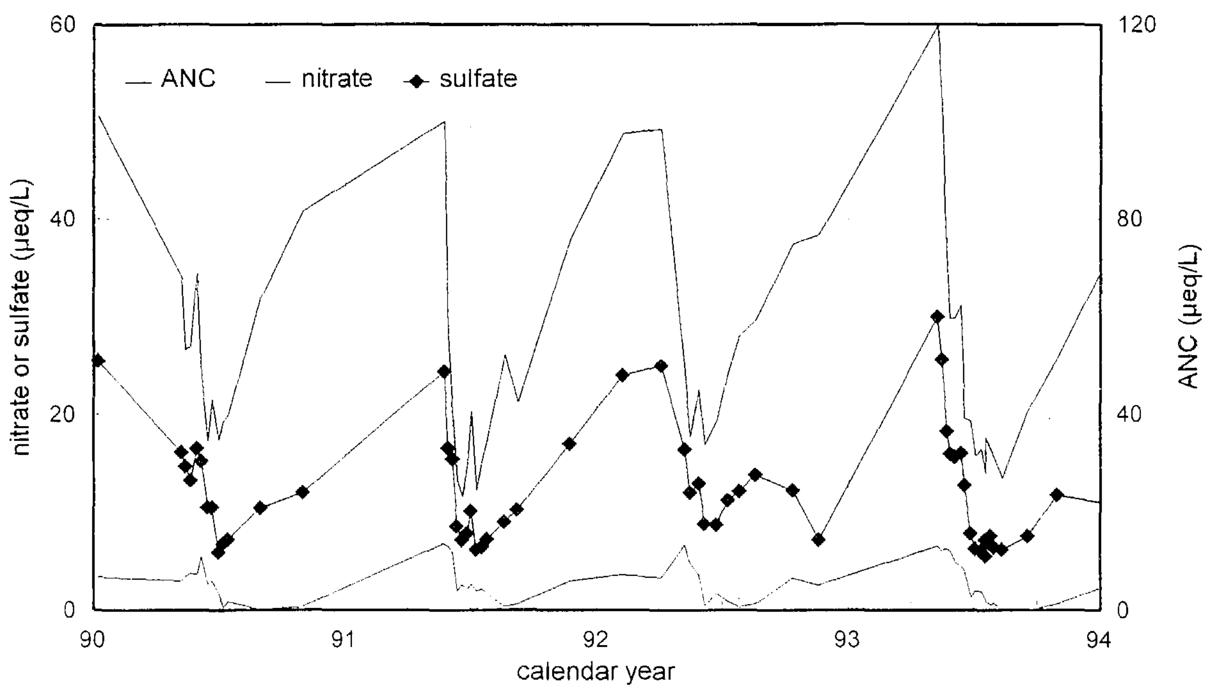

HEATHER LAKE
FALL OVERTURN CHEMISTRY
pH
7
6.5
6
5.5
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
UPPER MOSQUITO LAKE
FALL OVERTURN CHEMISTRY
pH
7.5
7
6.5
6
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
CRYSTAL LAKE (MINERAL KING)
FALL OVERTURN CHEMISTRY
pH
7
6.5
6
5.5
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
EMERALD LAKE
FALL OVERTURN CHEMISTRY
pH
7
6.5
6
5.5
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95

Figure I-139



(a)



(b)

Figure I-140

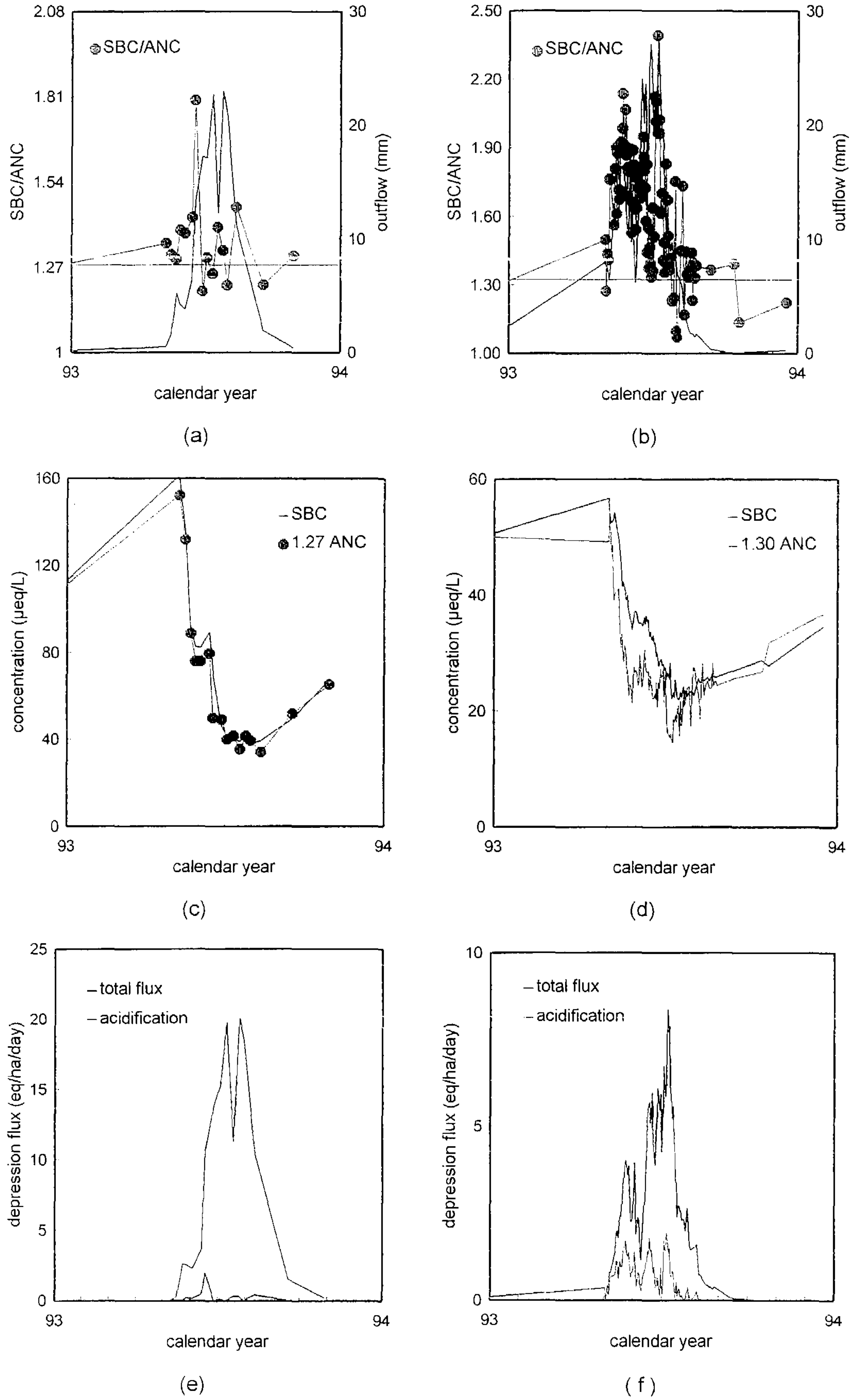
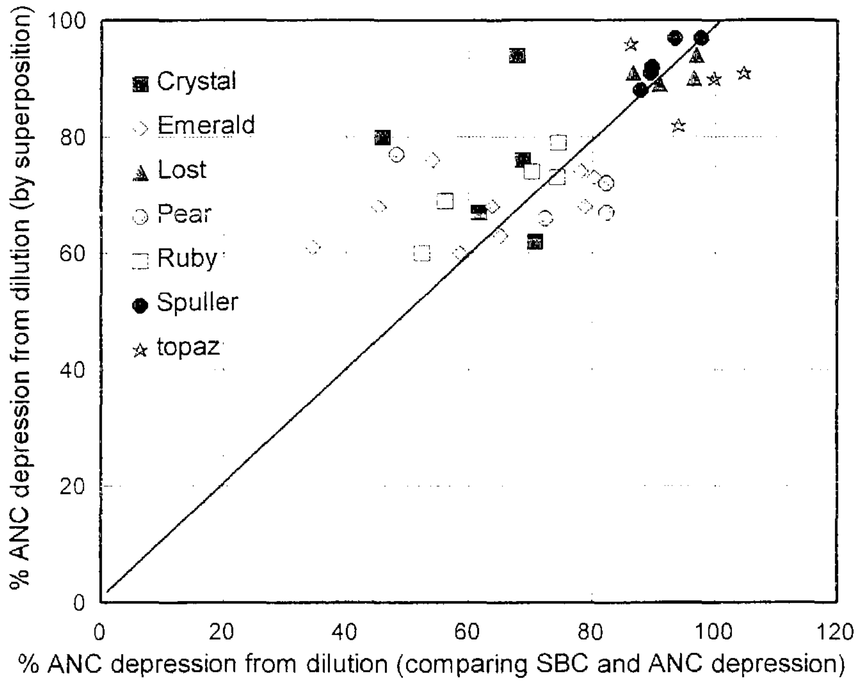
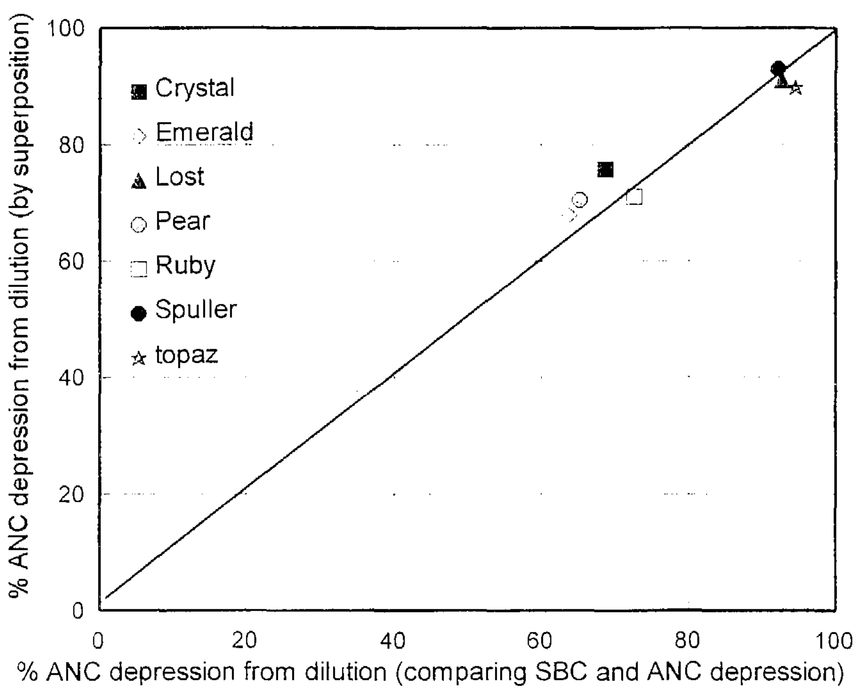

SBC/ANC
outflow (mm)
calendar year
(a)
SBC/ANC
outflow (mm)
calendar year
(b)
SBC
1.27 ANC
concentration (µeq/L)
calendar year
(c)
SBC
1.30 ANC
concentration (µeq/L)
calendar year
(d)
total flux
acidification
depression flux (eq/ha/day)
calendar year
(e)
total flux
acidification
depression flux (eq/ha/day)
calendar year
(f)

Figure I-141

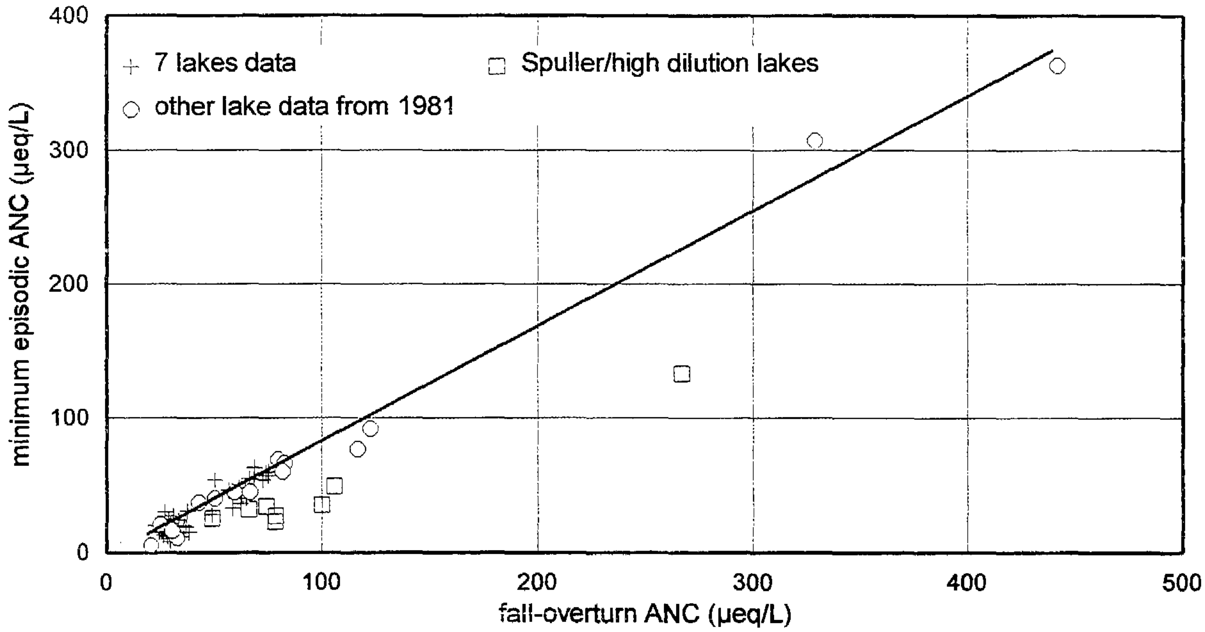


(a)

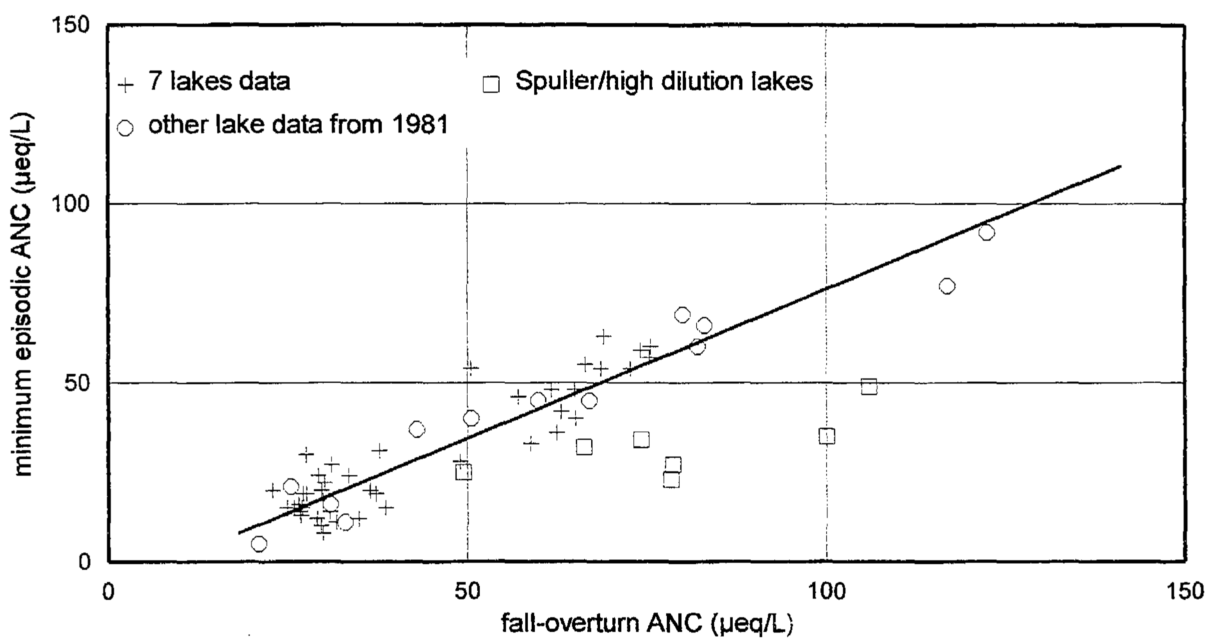


(b)

Figure I-142

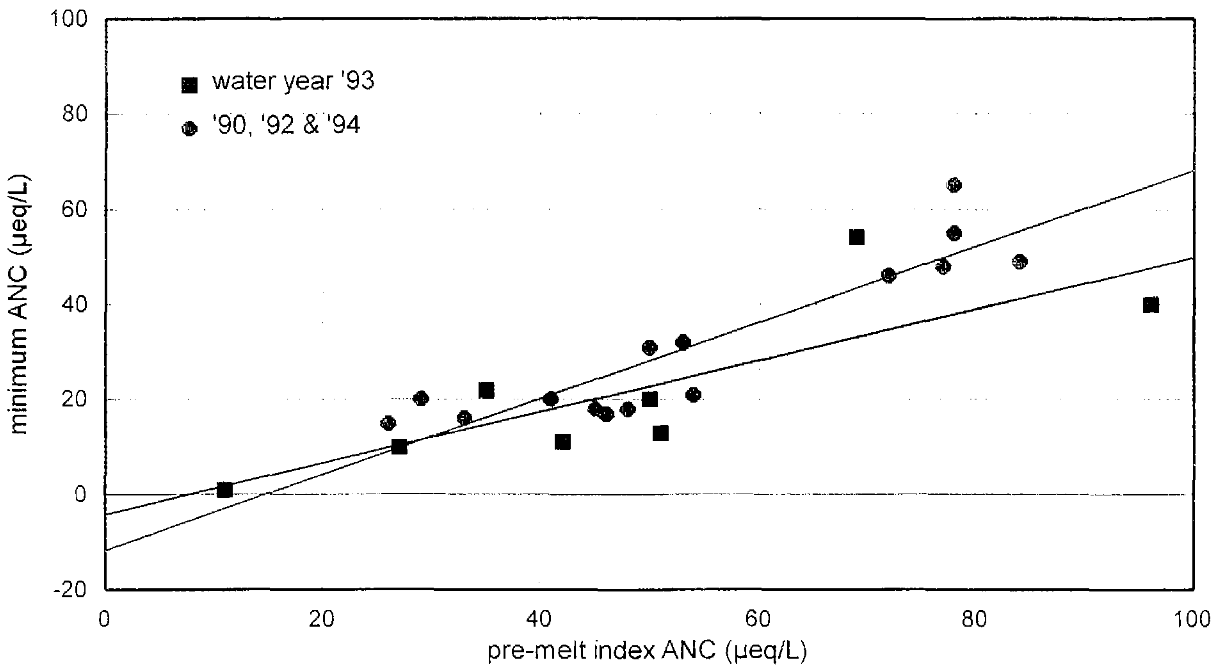


(a)



(b)

Figure I-143



100
80
60
40
20
0
-20
0
20
40
60
80
100
water year '93
'90, '92 & '94
minimum ANC (μeq/L)
pre-melt index ANC (μeq/L)

Figure I-144

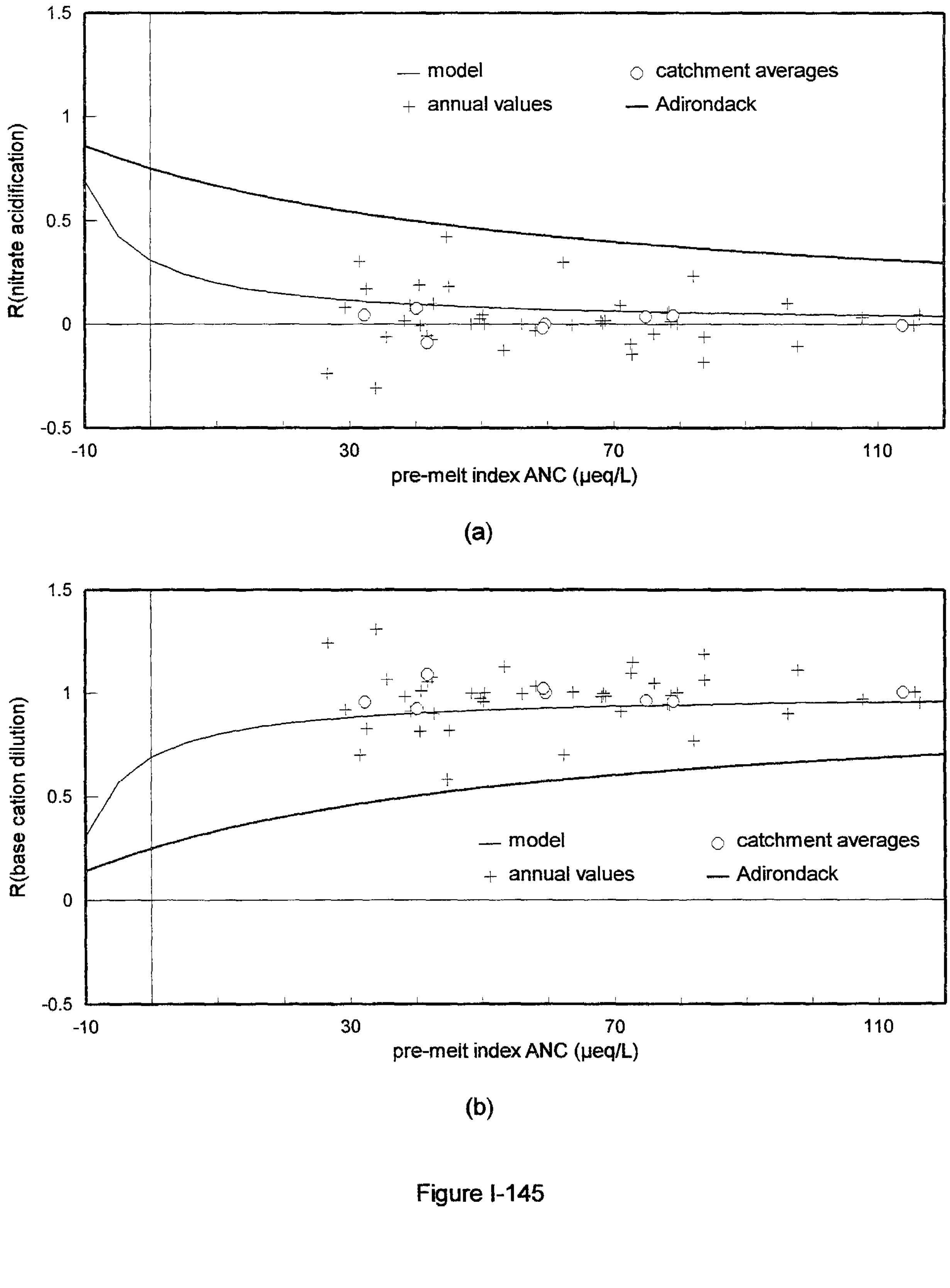
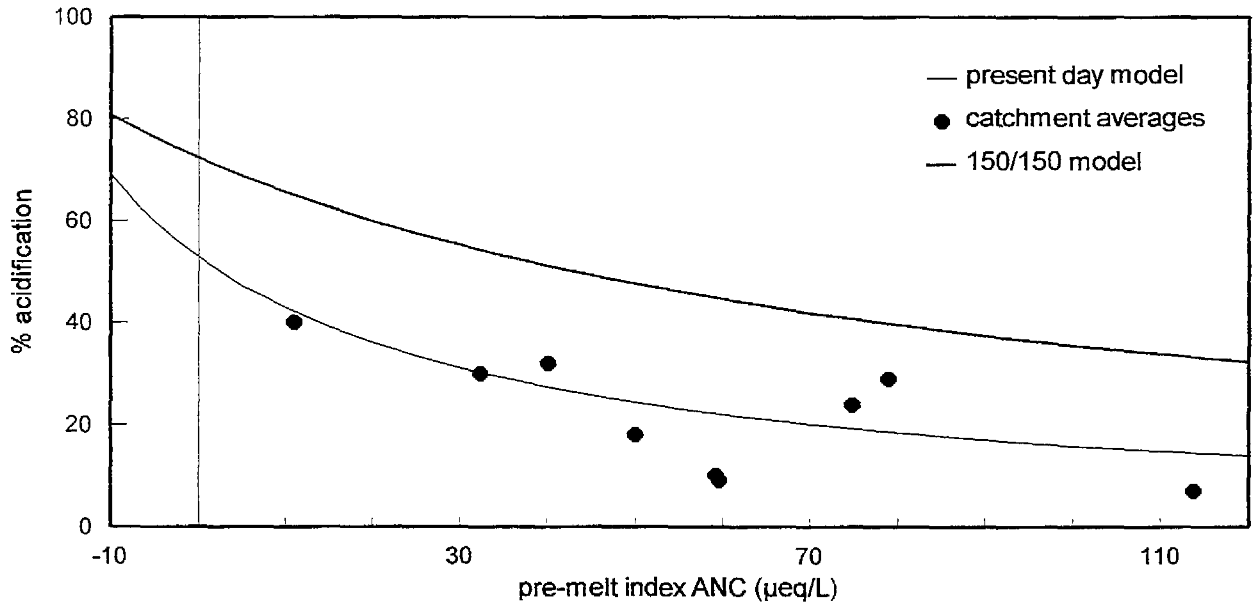
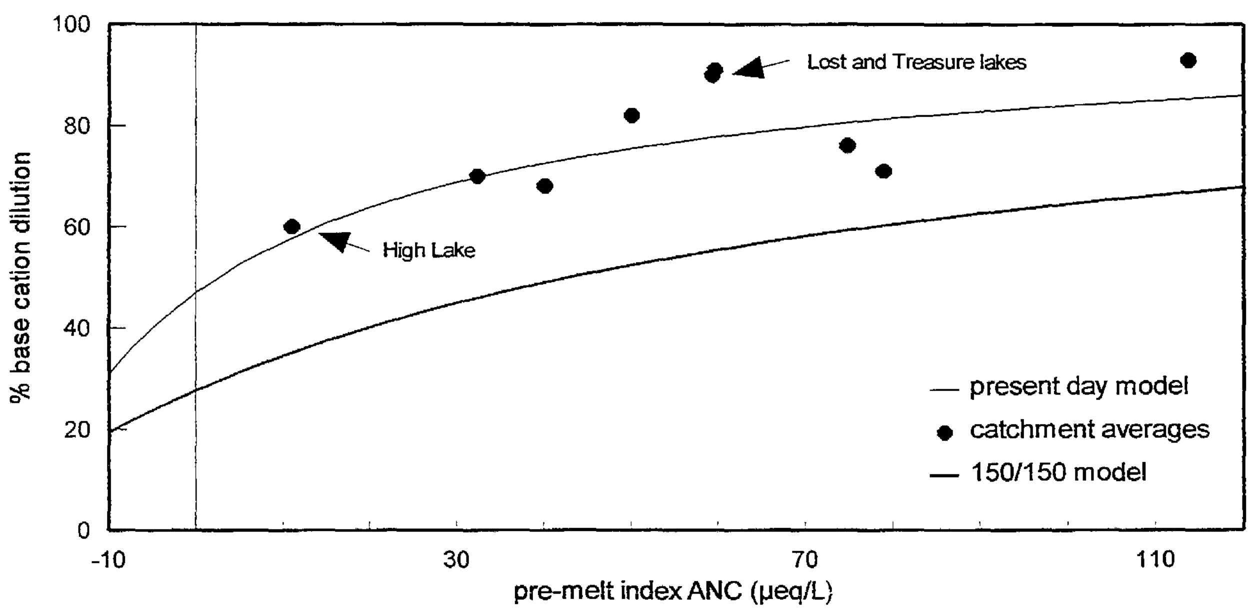

1.5
1
0.5
0
-0.5
R(nitrate acidification)
model
annual values
catchment averages
Adirondack
-10
30
70
110
pre-melt index ANC (µeq/L)
(a)
1.5
1
0.5
0
-0.5
R(base cation dilution)
model
annual values
catchment averages
Adirondack
-10
30
70
110
pre-melt index ANC (µeq/L)
(b)

Figure I-145

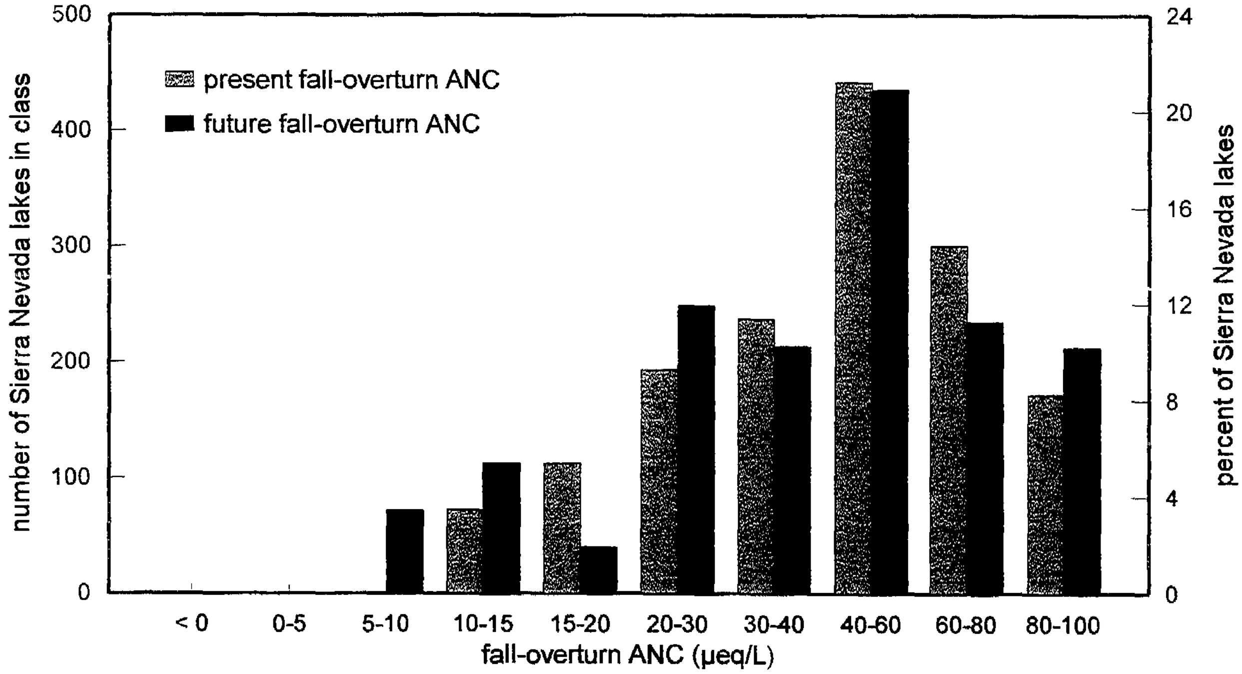


(a)

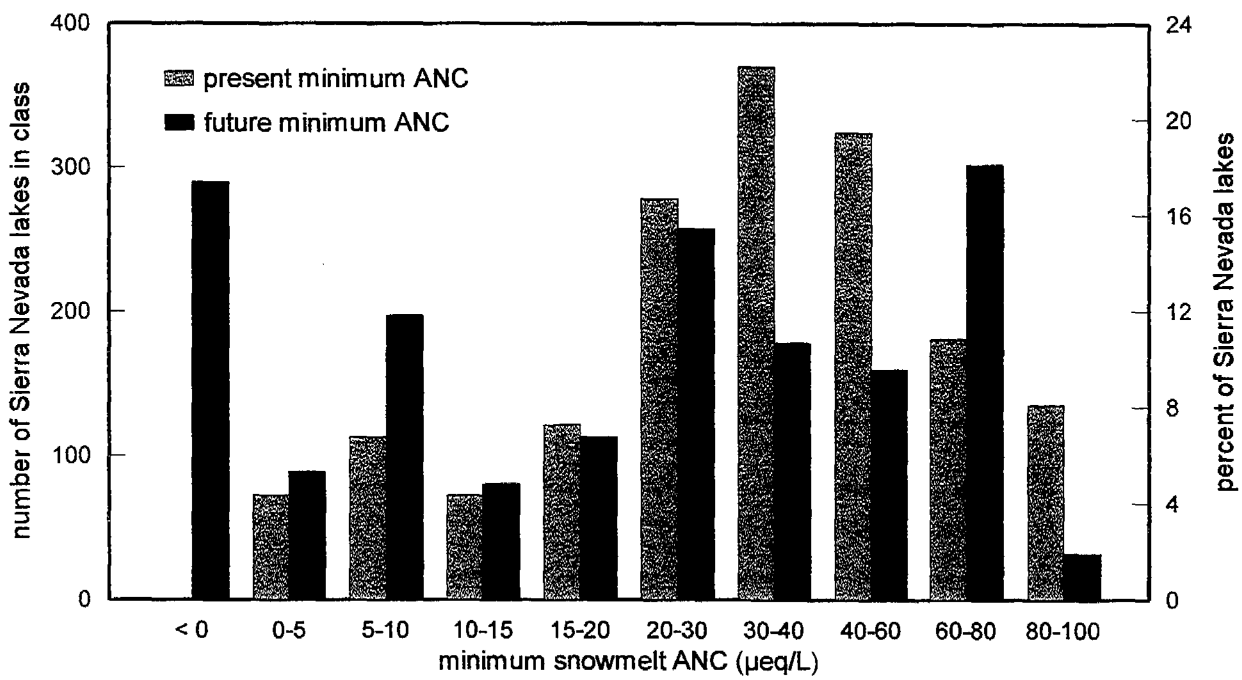


(b)

Figure I-146



(a)



(b)

Figure I-147

Chapter Two

Annual Water Balances of Eight High Elevation Catchments in the Sierra Nevada

by

James O. Sickman, Al Leydecker and John M. Melack

Chapter Two
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2. Chapter Two

2.1. Introduction

The water balance and hydrologic characteristics of the Sierra Nevada are crucial to our understanding of surface water acidification in high elevation watersheds. The water cycle controls the flow of solutes through the catchments and determines to a large extent the timing and extent of surface water acidification.

The annual water balance for a small catchment consists of the major hydrologic fluxes into and out of the catchment:

$$P = (Q + E + \Delta S + \varepsilon) \qquad (1)$$

where:

P is precipitation,
Q is surface water discharge,
E is water lost to evaporation,
ΔS is the change in water storage, and
ε is quantities not accounted for or error.

For the eight watersheds in this study these quantities include winter (December through March) and non-winter (April through November) precipitation, outflow discharge, evaporation, condensation, seepage and lake and groundwater storage. Precipitation and outflow discharge were directly measured. An areal model using meteorological data was used to estimate evaporative losses (Chapter Four). Changes in lake storage were small compared to precipitation and outflow and do not need to be accounted for in an annual water balance. Groundwater storage and seepage are much more difficult to determine than the other fluxes. A previous study at Emerald Lake has demonstrated that groundwater storage and release account for a small fraction of the annual water balance (Kattelmann and Elder 1991). In the present study we did not directly measure groundwater storage, but evaluated this component as part of the residual term in the water balance.

The major objectives for constructing water balances for a representative set of Sierran watersheds were:

1. Provide accurate volumes of inputs and losses of water to be combined with measurements of precipitation chemistry and stream chemistry in solute balances for a representative set of Sierran watersheds.

2. Describe the annual and interannual variability in the water cycle for high elevations of the Sierra Nevada.

In this chapter we present data on the major inputs and losses of water from seven headwater catchments and a moderate-sized river basin in the Sierra Nevada. For the Crystal Lake, Lost Lake, Pear Lake and Topaz Lake basins we have included data from water years 1990 through 1993. At Emerald Lake, Ruby Lake and Spuller Lake, water balances from 1990 through 1994 are included. Annual water budgets from the upper basin of the Marble Fork of the Kaweah River are presented for water years 1993 and 1994. A total of 33 annual water-balances were constructed. Detailed methods for precipitation measurement and outflow gauging are presented in this chapter; methods for evaporation calculations are discussed in Chapter IV. We will describe the annual, interannual and basin-to-basin variability in the timing of major inputs and losses of water to high elevation catchments of the Sierra Nevada. In addition, we discuss the accuracy of each water balance component and the likely uncertainty and bias associated with it.

2.2. Methods

2.2.1. Precipitation Measurements

Non-winter precipitation was measured in most watersheds with a tipping bucket rain gauge (Qualimetrics model 6011-b) from June through October during most years. The gauges were located in the basins, nearby the lake inlet or outlet. Exceptions were the Pear and Lost lake basins where rainfall data from Emerald Lake and Angora Lake basins were substituted respectively (Table II-1). Hourly rainfall was electronically recorded on a datalogger (Omnidata Easylogger or Omnidata Datapod). Precipitation during the period of April, May and November was measured in a variety of ways. At Emerald Lake and Mammoth Mountain, snowboards were used to sample small snowstorms during April and May. Large spring storms were sampled in the Emerald and Ruby lake watersheds by digging snowpits and sampling the fresh snow. When snowboard or snowpit data were unavailable, precipitation was estimated from the records of nearby meteorological stations. In Sequoia National Park precipitation was recorded at the Lodgepole Ranger Station, located at the mouth of the Tokopah Valley (5 km west of Emerald Lake, at an altitude of 2050 m). In the eastern Sierra, precipitation records were available from the U.S. Forest Service Office in Mammoth Lakes and at the Lake Mary store; both are located near the Crystal Lake watershed. (Lake Mary is located 2 km north-northeast of the outlet to Crystal Lake at an elevation of 2700 m. The Forest Service Office in Mammoth Lakes is located 7.5 km north-northwest of the Crystal Lake basin at an elevation of 2400 m). For Lost Lake, records from Alpine Meadows ski-area were used. Alpine Meadows is located along the north-west shore of Lake Tahoe and is about 30 km north of the Lost Lake basin. The heated tipping bucket rain/snow gauge was situated at an elevation of 2,164 m. Table II-1 summarizes the sources of data used for each watershed during the study. Large snowstorms (greater than 20 mm snow water-equivalence, i.e., SWE) in November were counted as winter precipitation and measured the following spring in our snowpack surveys.

Accumulated winter precipitation was measured by snowpack surveys conducted at maximum pack accumulation in late March or early April (Table II-2). Previous studies conducted at Emerald Lake have demonstrated that snow accumulates throughout the winter with little melt until spring (Kattelmann and Elder 1991). This approach to measuring winter precipitation has the added advantage that snowpack evaporation, during the period of December through March, is automatically compensated for, i.e., measured accumulation equals actual accumulation minus evaporation.

Basin-wide winter snowfall was determined from snow-depth surveys and measurements of snow density. Typically 2 to 4 transects starting at the lake-shore and running to the edge of the catchment, were measured. The transects were designed to be representative of the basins' topography including all categories of slopes, aspects and elevations. Along the transect, depths were measured with aluminum probes (graduated in centimeters) at intervals of 20 to 50 meters. At each location, from 3 to 5 individual measurements were made within a 2 to 10 meter circle. Thus, basin snow water-equivalence is based on hundreds of individual depth measurements (Table II-2). Areas without snowcover were not included in the transects.

Snow depths measured along transects were weighted and averaged according to the distance the transect covered. For example, if two transects were sampled in a basin, one covering a distance of 1000 meters and another covering a distance of 3000 meters, the mean depth of the first transect would contribute 25% to the basin-wide mean and the second transect would contribute 75% to this mean. Therefore, the basin-wide average was weighted in favor of longer transects, representing a larger percentage of watershed area.

Snow temperature and density were determined in snowpits dug to the ground, by hand, using aluminum or steel shovels. Over the five years of the study, snowpits ranged in depth from less than 1 meter to over 6 meters. Once dug, a vertical wall was created on a portion of the pit (using a plastic shovel) not exposed to direct sunlight. In each watershed from 2 to 4 snowpits were sampled. Snow density was measured in a vertical profile at 10 cm intervals using a wedge-shaped, stainless steel cutter and portable electronic balance. The cutters sampled 1000 cm^3 of snow and were calibrated to have less than 1% error in volume. To collect a sample for weighing, the cutter was pushed into the wall of the pit until it filled with snow. A flat metal blade was inserted along the open face of the cutter to cut a wedge of snow from the pack. The weight of the snow-wedge was then measured on the balance (tared for the cutter weight). Since the volume of the cutter was 1 liter, the density ($gm\ L^{-1}$) of the snow sample was its weight in grams. Values for each 10 cm interval were averaged to obtain a mean density for the pit.

Snow density was also determined with a Federal-type snow sampler. The sampler consists of various sections of aluminum tubing and a spring scale. Starting at the snow surface, tube is pushed all the way through the pack until it contacts the ground. Next the depth of snow is recorded and the snow-filled tube is removed from the pack. Its weight (tared for the tube weight) in inches of SWE is measured with a spring scale. Density was calculated by dividing SWE by the uncompacted snow depth of the sample. Individual pit and Federal determinations of snow density were averaged for each watershed to obtain a mean snow density for that watershed.

Average catchment SWE was calculated by multiplying basin-mean density by distance-weighted mean depth and correcting for snow-free areas. The percentage of snow-free area in each watershed was obtained from aerial photographs of the watersheds taken on or near the date of the surveys. Thus, estimates of SWE for each year are based on many, spatially distributed measurements of snowpack depth and density. Adding SWE to the amount of recorded non-winter precipitation yielded the total input of water for each catchment.

2.2.1.1. Accuracy of Precipitation Measurements

The uncertainty in measuring precipitation varied with its form (rain or snow) and the time of the year in which it fell (winter or non-winter seasons). In order to establish the uncertainty in annual precipitation quantities, we separated precipitation into two classes: winter snow and non-winter precipitation. The non-winter class was further divided into three sub-classes: Spring Rain/Snow, Summer Rain and Autumn Rain/Snow (Table II-3). These divisions were necessary because different techniques or combinations of techniques were used to estimate precipitation, i.e., snow surveys for winter snow, tipping buckets gauges for summer rain, snowboards, snowpits, rain gauges and nearby rainfall records for spring and autumn precipitation.

2.2.1.1.1. Non-winter Precipitation Measurements

Uncertainty in measuring rain during the months of June through September was dependent on the rain gauge accuracy and the fact that quantities were extrapolated from a single point to cover an entire watershed. The rain gauges used were accurate to ± 1%. Some gauges were equipped with Alter-shields (Emerald Lake, Spuller Lake, Angora Lake and Mammoth Mountain) to improve their efficiency during windy rain-events. Because of logistical constraints, non-winter precipitation estimates from some catchments, i.e., Lost Lake, Ruby Lake and Spuller Lake, have greater error than measurements at other study sites. Rain gauges at these sites were set up later in the summer and removed earlier in the autumn than at other catchments, requiring greater extrapolation of data from nearby stations.

The effect of rain-gauge density (i.e., km^2 per gauge) on the accuracy of basin-wide estimates of precipitation was reviewed by Winter (1981). His estimates of uncertainty for daily rainfall were ± 10% for a gauge density of 21 km^2/gauge and ± 4% at a density of 2.6 km^2/gauge. In our study the sampling density ranged from 9.5 km^2/gauge in the Marble Fork drainage to ca. 1.0 km^2/gauge at Spuller Lake basin. Based on these findings and those from Kattelmann and Elder (1991) we estimate that the uncertainty for summer precipitation measured in rain gauges was less than ± 5%, with no systematic bias.

In our companion report Melack et al. (1997) gaps in the precipitation record from spring and late autumn were not accounted for in estimates of annual precipitation. In that study volume-weighted mean chemistry, solute deposition and precipitation quantity were calculated only from storms actually sampled at each station. In the present report we accounted for all precipitation in a watershed.

In autumn, precipitation can fall as either rain or snow and was measured with rain gauges. Autumn rain measurements had an accuracy of less than ± 5%. However, autumn snow can fill the top of the gauge with snow and cause an underestimate of quantity. This problem is most likely to occur during large, storms in November. If rainfall records from nearby stations are available then the amount of under-sampling can be estimated. An additional problem is the decision of whether or not to account for autumn snow in the water balance when it falls or to assume the snow persists in the basin and is measured during the subsequent spring snow-survey. If this snow was counted when it fell and also measured as part of the basin snowpack, annual precipitation would be overestimated. In this study, large snowstorms that occurred during late October and November were assumed to be accounted for in the snowpack surveys of the following year. Given the errors from clogged rain gauges and the uncertainty of persistence of late-autumn snow, we estimated the error for autumn precipitation quantity at ± 5-10% (Table II-3). The magnitude of these errors is consistent with estimates obtained by other researchers in mountainous terrain (Kattelmann and Elder 1991, Williams and Melack 1997, Likens and Borman 1995). Smaller errors were estimated for catchments in the

Tokopah Valley (Emerald, Pear, Topaz) and Crystal Lake because rain gauges were left installed later into the autumn and rainfall records from nearby stations were available. In addition, these catchments had more frequent service visits (e.g., snow-clogged gauges were more often cleared).

Spring precipitation was difficult to measure since it was usually impossible to operate the rain-gauges during April and May. During April and May rain, at most sites, had to be estimated from quantities measured from nearby stations at lower elevations. However, at Emerald Lake and Mammoth Mountain, spring snow was routinely measured in shallow snowpits or with snowboards, but these measurements were unavailable for the other basins For spring snow at these sites, quantities were extrapolated from Emerald Lake, Mammoth Mountain or from the lower elevation Ranger stations at Lodgepole and Mammoth Lakes (see Table II-1). Overall these problems probably caused a slight underestimation of spring-time precipitation. All large spring storms were accounted for at all watersheds and most of the missed precipitation was from small rain or snow events that cumulatively deposited little water or solutes. Based on these facts and the results from other research conducted in montane catchments (Kattelmann and Elder 1991, Williams and Melack 1997, Likens and Borman 1995) we estimate the uncertainty in spring precipitation to range from ± 5-7.5%, with a small systematic underestimate which varied from year to year, but was probably less than 1% of annual precipitation (Table II-3). Availability of nearby rainfall records and snowboard and snowpit measurements of spring snowfall account for the lower error at the Tokopah Valley sites and Crystal Lake.

The overall uncertainty in the measurement of non-winter precipitation ranged from ca. ±9% to ±14% and was obtained by combining the errors from spring, summer and autumn measurements (Table II-3). The combined uncertainty was calculated by the root sum-square method:

$$E_{non\text{-}winter} = (E_{summer}^{2} + E_{spring}^{2} + E_{autumn}^{2})^{0.5} \qquad (2)$$

where:

$E_{nonwinter}$ is the uncertainty in estimates of annual non-winter precipitation,
E_{summer} is the uncertainty in summer precipitation measurements,
E_{spring} is the uncertainty in spring precipitation measurements, and
E_{autumn} is the uncertainty in autumn precipitation measurements.

The errors were not weighted on the basis of precipitation quantity since the weighting would vary for each water year and each catchment. This simplification had a very minor effect on estimates of annual precipitation error and additional precision was not warranted for several reasons: (1) the combined errors obtained from the root sum-square method are greater than any individual component error, (2) the individual component errors were similar, (3) the errors are similar to or greater than those obtained by other researchers using similar techniques (Kattelmann and Elder 1991, Williams and Melack 1997, Winter 1981), and (4) we were conservative in assigning errors to each component.

2.2.1.1.2. Winter Precipitation Measurements

Uncertainty in estimating winter precipitation by snow-surveys is caused by several factors. First, winter snow can melt or evaporate prior to the spring survey. This is especially true of snow on south-facing slopes in the watersheds. However, the amount of runoff from melting snow during the months of December through March (less lake-water displaced by snowfall on ice) was less than 1% of winter precipitation. Winter evaporative is not substantial (see Chapter Four) and was accounted for in the spring snow-survey (i.e., winter evaporation reduced the size of the spring snowpack). Therefore, calculated evaporation for December through March was not included in the annual evaporation estimate used in the water balances. This accounting method simplified calculations since a single snowpack SWE could be used for both water and solute balances (Chapter Three). The solute balance took into account only those hydrologic fluxes that influenced the movement of solutes into or out of the catchments. In the Sierra Nevada, winter evaporation probably has little or no effect on the quantity of solutes in the spring snowpack though it caused higher solute concentrations (4-13%) through evapoconcentration. In colder regions, solutes (particularly nitrogen compounds) can volatilize out of shallow (< 1 meter) snowpacks experiencing large temperature gradients (i.e., temperature differences greater than 50°C between the top and bottom of the pack) and high rates of sublimation (Pomeroy et al. 1998). These conditions do not occur in the Sierra Nevada, thus, winter sublimation of snow does not effect the solute budgets in the study catchments.

The major source of uncertainty with the snow surveys was the extrapolation of depths and densities measured at a few points to the larger watersheds. Snow-covered area was measured using aerial photography and showed little year to year variation. Snow depth had greater spatial variability than snow density and most of our effort during the surveys was focused on adequately determining the snow depths in the catchments (Table II-2). Hundreds of depth measurements were made throughout the watersheds in an effort to over the entire suite of slopes, aspects and elevations contained in the catchments. With the exception of south-facing slopes, snow accumulation is controlled by wind patterns during storms and basin topography including cliffs that sluff snow, avalanche paths and gullies and depressions that accumulate snow.

The accuracy of the SWE measurements was tested by comparisons to a terrain-classification model of SWE (Elder 1995) at four of the basins: Emerald, Ruby, Spuller and Topaz. In this model, SWE is distributed over a watershed on the basis of winter solar radiation, slope, elevation and surface characteristics such as vegetation. At Emerald the two methods agreed within ± 3% (Table II-4). At Ruby the difference between measured and modeled SWE was 3% in 1993 and 13% in 1994. Agreement was also good at Spuller with a 5% difference in 1993 and 2% in 1994. For 1993 at Crystal, the two techniques differed by 8%. On average, SWE determined with the distance-weighted method was within 5% of the more complicated and mechanistic snow-distribution model. Assuming modeled SWE is the true value, we estimate that our measurements of winter precipitation have an uncertainty of ± 5%. Since there were no major differences in the intensity of the snow surveys among the catchments the same error was assumed for study sites. Since winter snow is the dominant input of water to the Sierra Nevada, comprising from 80 to 95% of annual precipitation (Melack et al. 1997), most of the uncertainty in annual precipitation quantity is due to errors in measuring SWE.

2.2.2. Outflow Discharge Measurements

Gauging discharge in mountain streams presents many formidable challenges. The stream are difficult to reach because of their remote location and because they are buried under snow for many months of the year. The channels are steep and boulder-strewn with turbulent flows that usually precluded the use of current meters to measure flows. In addition, the watersheds in this study are located in Federally protected wilderness areas with restrictions on the construction of control structures.

Gauging stations were installed in the outlet streams of all catchments and on the Marble Fork River. Each station consisted of the following equipment:

1. Staff gauge securely fastened to a bank of the stream.
2. Two pressure transducers bolted to the stream bed.
3. Temperature sensor bolted to the stream bed.
4. Omnidata datalogger hung in a nearby tree or metal tower.

Stream stage (water depth recorded as transducer voltage) and temperature were continuously recorded on the datalogger. The stage and temperature sensors were scanned every five minutes. These readings were averaged over a longer interval for storage in non-volatile memory (EPROM). Early in the study, data from 3 five-minute scans were averaged and stored for a report interval of 15 minutes. In the autumn of 1990 the report interval was increased to one hour, i.e., twelve five-minute scans were averaged and recorded each hour. Staff gauge readings were made during each station visit. These readings were used to derive a mathematical relationship between transducer output (volts) and stream stage of the stream. This relationship was necessary for calculating discharge from a rating curve (i.e., the mathematical relationship between stage and discharge) and to insure that transducers are operating consistently and accurately.

To convert stage to discharge (cubic meters per second) a stage-discharge relationship was established for each outlet stream. At Emerald and Spuller lakes, weirs with known stage-discharge relationships were built in the outlet streams. At other sites the stage-discharge relationship was determined empirically. To establish this relationship discharge measurements were made on weekly to biweekly basis during snowmelt with occasional measurements over the remainder of the year. Because the rating curves were unstable over time, owing to changes in channel morphometry, discharge measurements were made each year (Table II-5).

The overall accuracy of the stage-discharge relationship depends on the hydraulic characteristics of the stream channel (e.g., slope, roughness, channel controls). The precise location of the station was decided by the availability of a site where desired characteristics were present. Of foremost importance was the presence of a channel control. Controls may be natural (e.g., small water fall, log dam or stream constriction) or man-made (e.g., weir or rock dam), but in all cases their function is to stabilize and sensitize the relationship between stage and discharge at the gauging site. Stream controls accomplish this, in part, by eliminating the effect of downstream conditions on the velocity of flow at the gauge and in maintaining a stable flow regime at the gauge. The degree of control affects the amount of stage change with discharge and therefore the sensitivity of the stage-discharge relationship. For example, a V-notch weir (such as the ones at Spuller and Emerald lakes) causes a large increase in water depth for a small increase in discharge.

At the other extreme, a broad obstruction e.g., a log or waterfall, will result in only a small increase in water depth for a large increase in discharge.

Other factors influenced our selection of gauging sections. Outlets to Sierran lakes frequently branch into several channels upon exiting the lake and gauging stations had to be located where the total outflow was confined in a single channel. However, this location had to be near the outlet of the lake to avoid measuring runoff from areas outside the catchment boundary. In general, we chose sites near the lake outlet where flow was confined to a single channel and where there was some sort of channel control and reduced turbulence.

Discharge measurements used for the stage-discharge relationships were determined from velocity-area profiles and dilution methods (Kilpatrick and Cobb 1985, Herschy 1978). Except at the Marble Fork station, dilution methods were the best and primary technique for determining discharge since the streams tended to be rather shallow, boulder-strewn and fairly turbulent, and generally unsuitable for using a current meter. At the Marble Fork station, dilution methods were impractical at all but the lowest flows, and the velocity-area method was used. A cable-way was built over the river from which an operator could safely make velocity measurements across the stream profile. Discharge was computed arithmetically from the velocity measurements and the river's cross sectional area using the mid-section method (Herschy 1978). The cross-section was divided into 10 to 15 sections and the area and mean velocity of each section independently measured. The discharge through each section was calculated as:

$$q = vd\,[(b_1+b_2) \div 2] \qquad (3)$$

where:

q is the discharge of the section ($m^3\ s^{-1}$),
v is the mean velocity in the section, usually estimated at a single vertical point 0.6d from the surface ($m\ s^{-1}$),
d is the depth of water where the velocity is measured (m),
b_1 is the distance to the next velocity point on one side of the vertical (m), and
b_2 is the distance to the next velocity point on the other side of the vertical (m).

The total discharge for the cross-section is the sum of the discharges for all sections.

Two dilution techniques were used to measure discharge: slug injection and constant injection. For slug injections a quantity of NaCl (a conservative tracer) was introduced mid-channel into a flowing stream and the changing concentration of the tracer sampled at a downstream location. Stream conductance was used as the measure of tracer concentration. Conductance was measured every five seconds using a battery powered meter and stopwatch from the initial rise in stream conductivity through the peak and until the return to background conductivity levels. From these readings (which usually spanned from 1 to 5 minutes) a time-concentration or response curve was developed. The discharge as measured by slug-in injection expressed as:

$$Q = (v \times c) / a_c \qquad (4)$$

where:

Q is stream discharge ($m^3\ s^{-1}$),

v is the volume of the injected slug (m^3),
c is the specific conductance of tracer injected ($\mu S\ cm^{-1}$), and
a_c is the area under the response curve ($\mu S\ cm^{-1}\ s^{-1}$).

The distance between the injection and sample points is critical to the accuracy of the method. Complete mixing of the tracer, both laterally and vertically, is required before measuring stream response; the area under the response curve will vary depending on the location of the conductivity sensor if mixing is incomplete. We therefore chose injection sites that were turbulent to facilitate mixing and sampling sites a sufficient distance downstream that allowed adequate mixing of the tracer. In general, the distance between injection and sample points varied from 50 to 300 meters; greater distances were required as discharged increased.

The continuous-injection dilution method is based upon the same principles as the slug injection technique except that, a tracer is continually injected at a constant rate over a period of minutes to hours. As the tracer is introduced the concentration of the tracer in the stream gradually rises and eventually reaches a plateau. At this point, an equilibrium between streamflow and tracer is established. Adequate mixing is also of critical importance, but is easier to insure by uniform conductance readings across the lateral extent of the stream. If mixing is observed to be incomplete one simply moves further downstream until uniform readings are obtained. Once the equilibrium conductance has been reached and uniform mixing established then discharge is calculated as:

$$Q = (i \times C) / c \qquad (5)$$

where:

Q is stream discharge ($m^3\ s^{-1}$),
i is the tracer injection rate ($m^3\ s^{-1}$),
C is the specific conductance of the injected tracer ($\mu S\ cm^{-1}$), and
c is the specific conductance of the stream at equilibrium (plateau) ($\mu S\ cm^{-1}$).

Salt tracer was introduced into the streams using a Mariotte-type, constant-rate injection device constructed out of a 20 liter polycarbonate carboy. The carboy was fitted with a spigot and a specially vented cap. The cap is designed such that air enters the carboy through a tube at a point slightly higher than the outlet spigot (Kilpatrick and Cobb 1985). As long as the fluid level in the tank remains above this point then outgoing solution is under constant atmospheric pressure or, in other words, under a constant head. The injection rate was measured by timing the emptying rate of the carboy which was graduated to indicate volume. The injection rate was varied by adjusting the spigot. Under field and laboratory conditions the injection rate of these devices varied less than 5% over the full range of carboy volume. The salt solution concentration and injection rate were adjusted to raise the conductance of streams by 10 to 20 $\mu S\ cm^{-1}$ above background level (usually $< 5\ \mu S\ cm^{-1}$).

Rating curves were derived from a mathematical fit between discharge measurements and stage. First, discharge rates were calculated from the salt dilutions and velocity-area profiles. Obvious outliers were discarded and measurements done on the same day at the same stage (usually 3 or 4 replicates) averaged. Next, plots of measured discharge and stage (either as staff gauge or transducer voltage) were drawn to graphically evaluate the relationship. Finally a log-log function was fitted to the data (Table II-5).

At Emerald and Spuller lakes, gauging of the outlet streams was improved by the installation of v-notch weirs during 1990. A v-notch weir has the ability to measure low discharges accurately, to cover a wide range of flows and has a stable stage-discharge relationship which is wholly dependent on geometry (Table II-6).

Both weirs were fully contracted, meaning that the v-notch did not occupy the full width of the stream channel. The v-opening of the weir at Spuller Lake had an angle of 120 degrees. At Emerald Lake the weir was a combination of a 90 degree v-notch and a rectangular opening. At all, but the highest discharges, streamflow was confined to the v-opening. When discharge peaks during snowmelt it can fill the v-opening and begin to flow out of the wider rectangular portion of the weir. The size of the v-notch was sufficient to gauge the vast majority of the flows encountered during the course of our study. Both weirs were constructed of fiberglass-coated plywood and attached to the stream-bed and bank using angle-iron, concrete and steel bolts. The wetted perimeter of the weirs was quarter-inch steel plate, honed to a sharp edge. This edge consisted of a narrow surface at a right angle to the upstream face of the plate and a 45-degree chamfer on the downstream edge. There was adequate fall of water to ensure that the structures would not be submerged at high flows and at no time during the study did discharge exceed weir capacity.

2.2.2.1. Gauging Histories

2.2.2.1.1. Crystal Lake Watershed

Gauging of the outlet stream was initiated on October 11, 1986. The station was located about 100 meters downstream from the lake in a pool above a small waterfall which acts as a control. The relatively large distance between the gauging station and lake was required by channel braiding and ponding immediately after the stream leaves the lake. Fortunately, because of the topography, the amount of gauged catchment is only slightly greater (i.e., 10 ha) than the watershed area that drains through the lake.

The original installation consisted of a datalogger, single pressure transducer (1 psi range or 0 to 2 feet) and wooden staff gauge. The transducer was positioned under a pile of rocks to hold it in place in the stream channel. By October 18, 1987 the transducer had become buried under sand and silt; the outlet stream at Crystal is underlain primarily by loose volcanic soils and not bedrock. It was moved on this date to a better location and a new stage-discharge relationship was established. Data were recorded at 15 minute intervals.

On August 31, 1990 the report interval for the datalogger was changed to 1 hour to simplify data analyses. One month later, on September 30, the original transducer (known as #1), again buried under silt, was moved and securely bolted onto a boulder in the stream along with a second, 1 psi transducer (known as #2). New stage-discharge relationships were established. A thermistor was also installed on this date which subsequently failed and was replaced on September 6, 1991.

In order to improve the accuracy of discharge measurements the stream control was augmented by the creation of a small rock dam on October 20, 1992. The dam caused the pool in which the transducers were installed to deepen and become more quiescent. New rating curves were begun after the dam was built. A new, more robust staff gauge was also installed on this date. Gauging of the outlet to Crystal Lake ceased on October 10, 1994 and the equipment was removed.

2.2.2.1.2. Emerald Lake Watershed

For the present study, gauging at the outlet to Emerald Lake began on November 15, 1989. Prior to this date a station was operated by the UCSB Geography Department (see Dozier et al. 1989 for details) from August 1985 until June 16, 1988. Earlier records collected by the U.S. Geological Survey beginning in October 1983 and extending into 1984 also exist. A staff gauge installed in late 1983 by the USGS has been in use to the present day.

On November 15, 1989 a second 1 psi transducer (known as #2) was installed in the stream-bed, and both transducers were bolted to bedrock. Data were recorded on an Easylogger hung in a nearby tree. Prior to this date the pressure transducer (known as #1) was held in place under a pile of rocks. On November 15, 1989 the original transducer failed and was replaced on October 19, 1990 with a new 5 psi transducer; a thermistor was also installed. Henceforth the remaining 1 psi transducer was known as #2 and the new 5 psi transducer as #1. The weir was completed and came into operation on this date; the datalogger was moved to another tree and the report interval changed from 15 minutes to 1 hour. During the following year, the thermistor failed and was replaced on November 8, 1991. In addition, the 1 psi transducer began to drift electronically in 1991 and the transducer:stage relationship had to be re-evaluated each year thereafter (Table II-6). This transducer was replaced in November 1995 with a new Stevens 2.5 PSI depth transmitter. Gauging at Emerald Lake continues to the present.

2.2.2.1.3. Lost Lake Watershed

The gauging station was installed on November 20, 1989. Two 1 psi transducers and a thermistor were bolted to the bed of the stream in a small pool upstream from a small waterfall which acted as a control. A temporary staff gauge was installed at this time. Data were recorded on an Easylogger hung in a nearby tree.

The Lost Lake gauging site was not in an ideal location because of the stream morphology. Within the first 40 meters, the outlet stream branches immediately after exiting the lake then rejoins into one channel and empties into a broad shallow pond. Downstream from this pond the channel becomes very steep with turbulent streamflow not conducive to gauging. The only practical location for the gauging station was the short stream-section downstream from the lake where flow was confined in a single channel. While not ideal, this location added less than 1 ha of area the drained catchment and we were able to develop an adequate stage-discharge relationship at the site.

Thermistors at this station were troublesome and replacements were installed each autumn for the next three years. On October 27, 1992 the thermistor was replaced for the last time and a permanent staff gauge installed. Gauging at the Lost Lake station was terminated in October 1994 when the station was removed from the watershed.

2.2.2.1.4. Pear Lake Watershed

From October 19, 1986 until October 21, 1990 the gauging station consisted of a single 1 psi transducer, temporary staff gauge and datalogger. The outlet to Pear Lake presented the same gauging problems as the Lost Lake outflow. Stream branching and pooling constrained the location of the gauging section. Good gauging sections exist a couple of hundred meters downstream from the lake, but would have introduced a large amount of atypical terrain into the drainage area. The location chosen for the transducer was a short, narrow and rather steep section of stream between two pools located about 20 meters from the lake outlet. The transducer was buried under rocks to hold it in the stream-bed. A small waterfall provided control for this section.

By 1990 it was clear that the transducer location at Pear Lake was unsatisfactory. Snowmelt hydrographs exhibited an unusually steep rise and fall and salt dilution gauging was very difficult to conduct in this short, steep section of stream. Therefore, in October 1990 a second 1 psi transducer (known as #2) was installed (bolted to bedrock) in a broad, shallow pool below the original transducer (#1). A thermistor was also installed at this site. The new transducer recorded a normal snowmelt hydrograph that closely matched that at Emerald Lake. It was therefore used to calculate discharge at Pear Lake and operation of the original transducer was abandoned. As at Lost Lake, the thermistor installed at Pear Lake was defective. It was replaced and a permanent staff gauge installed in November 1991.

Despite the new transducer, review of the salt-dilution data from 1991 indicated continuing difficulties in accurately measuring flow. It was decided that future discharge measurements would be made in the outlet stream after it split into two distinct channels. This split occurs about 20 meters from the lake outlet and the resultant channels were much more conducive to dilution gauging. Flows in the channels were summed and then used derive the stage-discharge relationship. In addition, constant-injection dilutions were conducted with success in the small pool immediately downstream from the lake outlet.

Precipitation measurements at Pear Lake were terminated at the end of water year 1993, but gauging of the outflow stream continued until October 1994. On October 21, 1993 both transducers and the thermistor were moved to the small pool at the outlet of the lake. Because of our success with the constant injection technique, a good and fairly sensitive stage-discharge relationship was developed for this site. The gauging station was removed in September 1995.

2.2.2.1.5. Ruby Lake Watershed

A gauging station was installed on October 12, 1986. It consisted of a single 5 psi transducer, datalogger and temporary staff gauge. It was located in a small pool about 100 meters downstream from the lake. The control at this pool was improved by creation of a small rock dam. The gauging station at Ruby had to be relatively far from the lake because of ponding and waterfalls immediately downstream from the outlet. Despite this distance, only about 20 ha was added to the gauged drainage basin.

Until 1990 the only significant changes at the station were the replacement of the ruler on the temporary staff gauge (November 4, 1989) and changing the report interval from 15 minute to hourly (August 29, 1990). On October 29, 1990 a second transducer (1 psi, known as #2) and a thermistor were added to the station. They were bolted to a large boulder in the stream. The old transducer (#1) was inspected and re-buried under rocks in approximately the same location. The only other significant work done on this station was the replacement of the thermistor and staff gauge on October 11, 1992.

Starting in the month of September 1991, the original transducer (#1) began to behave erratically. This variability continued for a couple of months and then stopped until the following June when it began again and continued thereafter. Because of the erratic behavior of transducer #1, transducer #2 was used to calculate discharge for water years 1992, 1993 and 1994. Gauging of the outlet to Ruby Lake continues to the present.

2.2.2.1.6. Spuller Lake Watershed

The gauging station was installed on October 17, 1989. The station consisted of two-1 psi transducers bolted to the stream-bed and a temporary staff gauge. They were placed in a modest-sized pool that emptied over a small waterfall which acted as a control. The logging interval was set at 15 minutes and then changed to hourly on August 30, 1990. During the first year of operation the stage-discharge relationship was established using slug-injection measurements. However, a faulty conductance meter was used and the measurements were unreliable. The stage discharge relationship was unacceptable (Table II-5) and an approximate rating curve, based on curves for 1 psi transducers at other stations, was used instead. Peak snowmelt discharges, base flows and annual discharge derived from the Spuller Lake weir for similar water years (i.e., 1992 and 1994) were also used to reconstruct 1990 data (Table II-6).

A v-notch weir was constructed in the outlet stream on October 5, 1990. A thermistor was installed at this time. Because the outlet channel is underlain by glacial moraine and the weir anchored to marginal boulders instead of bedrock, sealing the edges of the weir proved difficult. Despite much effort a small leak was always present during the course of the study. The impact of the leak on estimates of discharge from the Spuller Lake basin are discussed in Section 2.2.2.2. which deals with gauging accuracy.

The original thermistor was faulty and was replaced in September 1991 and again in August 1992. On September 26, 1991 a new staff gauge was installed and another gauge placed on the weir. Because the pool that formed behind the weir was nearly 2 feet deep and the upper operational limit of the 1 psi transducers was 2.3 feet, a third transducer, with an operating range of 5 feet (2.5 psi), was installed in October 1992. The gauging station at Spuller Lake ceased operation at the end of 1996 and was removed in October 1997.

2.2.2.1.7. Topaz Lake Watershed

The gauging station originally consisted of a datalogger, 5 psi transducer and temporary staff gauge and was installed on October 18, 1986. Because of the lack of trees near the outlet stream the choice of suitable gauging locations was limited. The site chosen was a small and rather shallow pool with a nearby tree about 100 meters from the lake outlet. The next tree along the stream was 300 meters downstream from this site. Small waterfalls fed and emptied the pool the level of which ranged in depth from a few centimeters to 50 cm below the inlet waterfall. Since much of the pool was shallow, the transducer was placed below the waterfall to ensure it was submerged at the widest possible range of stage heights. It was felt that the relatively large range of depths measurable at this location would offset inaccuracies caused by turbulent flows.

Data-logging intervals were originally set to 15 minutes and then changed to every hour on October 20, 1990. On this date a second transducer (1 psi, known as #2) was installed in a relatively deep portion of the pool, downstream and away from the inlet waterfall. A small rock dam was built in the pool to increase the depth of water over the transducers and to act as a channel control. A thermistor was installed on this date and which subsequently failed and was replaced the following year (November 1991) when a permanent staff gauge was installed.

The gauging station ran smoothly from late 1991 until February 1994 when the stream became buried with ice and debris from a flash flood. The flood was caused by the collapse of a snow dam that had formed in a narrow upstream gorge. During the winter of 1994, the outflow to Topaz Lake was dry and the gorge slowly filled with snow. In February, a large storm deposited about 2 meters of the snow on the ice-covered surface of Topaz Lake. The snow load caused the ice on the lake to settle and which forced water out of the lake and into the blocked outlet channel. Water built up in the gorge until the point that the snow-dam failed and a torrent of water, ice, sand and rocks rushed downstream. The flood scoured the channel for a distance of about 200 meters and then excited the channel and flowed over the snowpack surface leaving debris from pebbles up to small cobble (20 cm) on top of the snow. The transducer pool was buried under this debris and the stage-discharge relationship greatly altered. Active gauging ended on this date.

2.2.2.2. Accuracy of Stream Gauging

The most accurate method for measuring stream flow is by direct volumetric measurement. With all other methods there is a difference between measured and true flow. However, certain techniques of measuring streamflow have less uncertainty than others. A well constructed weir will more accurately measure streamflow than flows derived from velocity-area profiles. Discharge determined by constant-injection of tracer should have less error than flows measured by slug injections. In the present study several techniques with varying accuracy were used to measure streamflow.

The stage-discharge relationship for a weir is based solely on the physical characteristics of the structure which can be precisely controlled during construction. Weirs can be checked by collecting and measuring volumetrically (at low to moderate discharge) the water passing over them as a nearly absolute judgment of their accuracy. The error for a single determination of flow in a v-notch weir may also be estimated by the following equation from Herschy (1978):

$$X'_q = \pm (X'^2_c + X'^2_b + \beta^2\, X'H^2)^{0.5} \qquad (6)$$

where:

X'_q is the percentage random uncertainty of a single determination of discharge,
X'_c is the percentage random uncertainty in the coefficients of discharge (i.e., a, the coefficient from the equation that describes the stage-discharge relationship for the weir which is based on ISO 1438 standards),
X'_b is the percentage random uncertainty in the length of the weir crest (i.e., wetted perimeter), and
$X'H$ is the percentage random uncertainty in the measurement of gauged head. This term includes error from the pressure transducers and the error for the regression between transducer voltage and depth of flow in the weir, and

β is the exponent of H in the weir equation (e.g., $q = aH^{\beta}$, see Table II-6)

For the weirs at Emerald and Spuller lakes the errors in the coefficients of discharge (X'_c) and the lengths of the crest (X'_b) are small (i.e., less than 1%) because they are based on the physical accuracy of the weirs geometry and the weirs were built to high tolerances. The largest component in the error equation stems from inaccuracies in the measurement of stage height (X'H). Errors in stage measurements include the uncertainty of transducer readings and uncertainty in the conversion of transducer voltage into stage heights using a regression equation. For the weir at Emerald Lake the error in discharge for the 5 psi transducer is:

$$X'_q = \pm (1^2 + 0.1^2 + (2.5^2 * (2.8 + 0.84)^2))^{0.5}$$
$$X'_q = \pm (2 + 0.01 + 19.50)^{0.5}$$
$$X'_q = \pm 4.64\ \%$$

where:

$X'_c = 1.0\%$ (Herschy 1978),
$X'_b = 1.0\%$,
$X'h = 2.8\ \%$ (error for the 5 psi transducer) + 0.84% (error for the regression between transducer voltage and stage height) = 3.64%, and
$\beta = 2.5$.

For the weir at Spuller Lake, the error for the 1 psi transducer would be:

$$X'_q = \pm (1^2 + 0.1^2 + (2.5^2 * (3.3 + 2.1)^2))^{0.5}$$
$$X'_q = \pm (2 + 0.01 + 35.41)^{0.5}$$
$$X'_q = \pm 6.12\ \%$$

where:

$X'_c = 1.0\%$ (Herschy 1975),
$X'_b = 1.0\%$,
$X'h = 3.3\ \%$ (error for the 1 psi transducer) + 2.10% (error for the regression between transducer voltage and stage height) = 5.40%, and
$\beta = 2.5$.

From the above calculations it is clear that properly constructed and installed weirs are very accurate for determining stream discharge and have an uncertainty of about ± 5%. Flow uncertainty is slightly less at Emerald Lake owing to a slightly more accurate transducer and better relationship between transducer voltage and stage height. More error is found in the voltage-stage relationship at Spuller Lake because the transducers are located in a relatively turbulent portion of the pool formed behind the weir. At Emerald Lake the transducer is in a quiescent portion of the pool.

Several methods for determining the error for dilution gauging are possible. In a similar fashion to determination of weir error, the random errors for dilution gauging may be combined by the root-sum-square method (Herschy 1978). However, with dilution gauging there are many possible random errors (e.g., errors in measurements of volumes, errors in determination of conductance and temperature, errors introduced by incomplete mixing of tracer etc.) in addition to errors in stage measurements. The large number of variables plus the incertitude in assigning a random uncertainty to each variable, makes this method cumbersome and yields results that are at best a guess. A better method, and the one used in this report, is to compare flow determinations made with dilution techniques to flows measured by weirs. This analysis was possible starting in 1990 at Emerald and Spuller lakes. The hydrologic conditions for these streams and their drainage basins are similar to those found at the other study sites, therefore results from the analysis at Emerald and Spuller lakes should be applicable to the other study sites as well.

To assess dilution-gauging error, comparisons between the methods were made in two ways. First, comparisons were made between instantaneous measurements of discharge from replicate salt-dilutions (both slug and constant injection) and the weir. Second, rating curves were calculated using dilution-measured discharge for Emerald and Spuller outflows and used to convert hourly transducer readings into daily, monthly and yearly flows for water year 1993 and compared to those computed using the weir equations. In all cases, weir-derived discharge is treated as the true discharge and errors are expressed in terms of weir-derived flow.

At Emerald Lake a sufficient number of constant-injection measurements were made so that the error for each of the two salt-dilution techniques could be separately determined. Only a few constant-injections measurements were done at Spuller Lake so they were combined with the slug-injections measurements in the error analysis. Figure II-1 shows the relationship between dilution-derived discharge and weir derived discharge for Emerald Lake outflow during the period of 1991-1994. There were twenty-seven sets of measurements using slug-injection and 15 made by constant-injection. Slug-injections were made over a wider range of flows than constant-injections. For both techniques the relationship to weir-derived discharge is linear and very similar to a 1:1 relationship with r^2 value of 0.94 for slug-injections and 0.99 for constant-injections. For both regressions the slope of the equations were not significantly different than 1 ($p<0.01$) nor were the intercepts significantly different from zero ($p<0.01$). There was no systematic error in either technique; points fall above and below the 1:1 line with similar frequency. However, the standard error for flow determination with slug-injection is ± 20%, more than 3 times greater than the ± 6.5% error for constant-injection.

When a rating curve developed from dilution-measured flows (both slug and constant-injection) was used to calculate daily, monthly and yearly discharge there was better agreement with weir-derived discharges (Figure II-2). Estimates of daily and monthly flows showed good agreement between the techniques. Errors in dilution-measured discharge at both lakes were greatest at high flows (Figure II-3). Annual discharge measured by the two methods differed by about five percent.

It is not surprising that dilution techniques overestimate discharge at high flows. One of the principal errors in the slug-injection technique is the recording of the slug-response-curve. At high flows, stream velocities are greater and the distance required for adequate tracer mixing increases. Stream conductivities recorded at 5 second intervals were probably too infrequent to adequately quantify the response curve and "missed" some of the tracer. Missed tracer would cause discharge to be overestimated since the area under the response curve was under-estimated. Also, inadequate mixing would tend to cause underestimates in the response-curve area since conductance measurements were made near the stream banks and not at mid-stream where tracer concentrations are typically highest.

Dilution measurements also overestimated discharge at Spuller Lake, but the error was larger and systematic (Figures II-3 and II-4). In all, but one of twenty-three comparisons between the two methods, dilution-derived discharge was higher. At the highest discharge, the dilution techniques overestimated daily flow at Spuller by 25%; at Emerald Lake the overestimate at high flows was ca. 6% (Figure II-3). The standard error of the estimate of dilution-derived daily flow at Spuller Lake was ± 9.6 %, and the r^2 value for the relationship was 0.92 (Figure II-4). The slope and intercept were significantly different from 1 and zero respectively at the $p<0.05$ level.

The relatively large discrepancy between dilution-derived and weir-derived flow at Spuller Lake has two possible explanations: dilution measurements systematically overestimates discharge or the weir systematically underestimates discharge. The inherent accuracy of v-notch weirs and field checks of flow through the Spuller weir at low and modest flows (Figure II-4) would seem to discount the weir as an explanation, however the weir did leak slightly where it contacted the stream-bed. From visual inspections of the leak, however, the amount of water not measured by the weir seemed very small compared to the amount flowing through the weir.

It is more likely that the systematic error is due to problems with the slug-injection measurements than with the weir. Some of the dilution measurements were done in the large pool formed behind the weir. Since storage of water in the pool was large relative to streamflow, tracer may have been trapped in the pool and missed at the downstream measuring site. Moreover, when slug-dilutions were done in downstream sections, high flow velocities were often encountered (owing to the steep slope of the channel) which made it difficult to describe the response curve with 5 second readings of conductivity, i.e., some tracer was probably missed. Both of these problems would systematically overestimate flow. With constant-injections, including the weir-pool in the measured section should not introduce systematic errors since equilibrium and complete mixing could be assured with adequate conductivity readings.

When dilution based flows were used in a rating curve to calculate daily, monthly and yearly flows at Spuller Lake, a large overestimate of discharge was found (Figure II-5). Dilution-derived flows were greater than weir-derived flows on a daily basis with the largest discrepancies occurring during peak runoff periods (Figure II-3). Annual flow determined from the dilution-based rating curve was 23% greater than annual flow through the weir.

Based on the results from comparisons of dilution-based and weir-based discharge, it is difficult to assign a precise uncertainty for the dilution measurements in this study. However, a range of probable values can be given. For the average of 3 or 4 replicate slug-injection determinations of discharge there is an uncertainty of between ± 10 to 20%. [For replicate slug-injections measurements of discharge made at a constant stage on the same date, the standard error ranged from less than ± 1% to more than ± 40%, with most errors in the range of ± 5% to ± 15% (Figure II-6)]. The uncertainty of single measurement of flow using the slug-injection method can be larger than ± 50%. When replicate determinations of discharge (made at a constant stage with slug-injections) are averaged and combined with constant-injection measurements to construct a rating curve, accuracy improves since most of the random errors in the slug-injection method cancel and the constant-injection measurements have less uncertainty. For determinations of daily discharge, uncertainty in the range of ± 5% to ± 25% can be expected with the greatest error occurring where dilution-gauging conditions are poor i.e., high velocity flows. Rating curves based solely on constant-injection measurements yield an uncertainty of about ± 10% for daily flows, however, too few constant-injection measurements were made at the study sites to construct rating curves that spanned the complete range of measured flows.

We estimated annual discharge error for each site during water years 1990 through 1994 (Table II-7) based on the above findings. In the analysis we assumed maximum and minimum annual discharge errors of ± 25% and ± 10%, respectively, when dilution techniques were used as the basis of rating curves. These values were based on the comparisons of annual discharge made during 1993 at Spuller and Emerald lakes (Figures II-5 and II-2). At Spuller Lake, dilution-based annual discharge differed from weir based annual discharge by 23.4%; at Emerald Lake the difference between the two methods was 5.0 %. In assigning errors we took into account the suitability of each stream to dilution gauging (i.e., channel braiding, mixing lengths, transducer placement etc..) and the percentage of measurements made with the more accurate constant-injection method. Sites where gauging was more problematic, such as Pear and Lost lakes, were assigned the highest uncertainty. Similarly, greater errors were assumed for annual discharge during 1990 and 1991 when we relied most heavily on slug-injection methods. The errors at Emerald and Spuller lakes for water years 1991 through 1994 are based on the accuracy of the weirs. Overall, we feel the error estimates are conservative.

The best method for measuring annual discharge from high-elevation catchments in the Sierra Nevada is the use of flow-measuring structures such as weirs. Uncertainty in weir-based discharge was on the order of ± 5% in the present study (Table II-7). The accuracy of weir-based discharge was effected by the placement of the transducers, with better results achieved when stage measurements were made under quiescent conditions. Dilution-gauging techniques using salt as a tracer are useful for gauging mountain streams, but must be conducted with great care. Under ideal conditions, errors in daily discharge estimates of about ± 10 % can be expected (e.g., Ruby and Crystal lakes). Under non-ideal conditions systematic overestimates of flow occur and the uncertainty in daily discharge can rise to ± 25% (e.g., Pear Lake).

2.3. Results and Discussion

2.3.1. Precipitation

In the water balance, snow that fell during the period from December through May was classified as winter deposition. Precipitation (both snow and rain) that fell during the period from June though November was classified as non-winter precipitation. Exceptions to these rules were rain events in May which were classified as non-winter precipitation and large snow-events in November that were classified as snow-deposition. The logic for these dichotomies is that precipitation that falls as snow during May and November (large storms only) is chemically, similar to winter snow while, rain that falls during May and November is chemically more similar to summer or autumn rain.

Annual variability in precipitation was large during the study. For the ten year record at Emerald Lake, annual non-winter precipitation varied from less than 50 mm to nearly 250 mm (Figure II-8). Snow deposition ranged from 600 mm in water year 1990 to over 2000 mm during water years 1986 and 1993 (Figure II-7). During water year 1993, non-winter precipitation at Emerald Lake was large compared to sites in the eastern Sierra Nevada and Lake Tahoe region because of a series of spring storms that dropped snow in the colder eastern and northern Sierra, but rain in the warmer Tokopah Valley. In 1993 the period from mid June through mid September was very dry for the Emerald Lake basin and the entire Sierran region. Less than 5 mm of precipitation was recorded during this time period at any of the study sites.

At Crystal Lake annual non-winter precipitation varied from 63 mm to over 120 mm during the period of 1987 through 1993 (Figure II-8). Snow deposition for the period ranged from 600 mm to 900 mm during the relatively dry period of 1987 though 1992, but was 2 to 3 times greater during 1993; ca. 1800 mm (Figure II-8)

Non-winter precipitation at Lost Lake ranged from 108 mm in 1991 to less than 30 mm during 1993 (Figure II-9). Snow deposition at Lost Lake was large compared to other sites. Annual deposition at Lost Lake varied by more than a factor of 3, and Lost Lake usually had the highest snow deposition among the study sites (Figure II-9). Because of the catchment's topography and the prevailing wind pattern, large amounts of snow blow into this basin from terrain outside the watershed. Snow depths measured in 1993 exceeded 10 meters in many spots, and the average depth was over 7 meters. Similar snow depths are usually confined to areas below cliffs in other watersheds, but were found throughout the Lost Lake catchment in terrain that is rolling. Hilltop areas adjacent to the catchment probably supply most of this snow as evidenced by their snow-free condition during our spring surveys.

Non-winter precipitation measured at Emerald Lake was used at Pear Lake (Figure II-10). SWE ranged from 600 to 800 mm during the drought years of 1987 through 1992 and reached 2000 mm during the wet winter of 1993.

At Ruby Lake non-winter precipitation varied from 44 mm in 1993 to over 180 mm during 1987 (Figure II-11). Snow deposition from 1987 through 1992 ranged from about 550 to 650 mm. The wet winter of 1993 deposited over 1300 mm of precipitation as snow (Figure II-11). Snow deposition in 1994 was similar to that in the drought years.

Year to year variability in non-winter precipitation at Spuller Lake was large, ranging from nearly 190 mm during 1992 to less than 50 mm in 1993 (Figure II-12). The dry winters in 1990 through 1992 and 1994 that had SWE of ca. 600 to 900 mm; during the wet winter of 1993 SWE was about 2000 mm.

The Topaz Lake watershed received nearly the same amount of non-winter precipitation as did Emerald Lake (Figure II-13). This is partly a result of using spring and late-autumn precipitation totals measured at Emerald Lake for the Topaz water balance. Snow deposition at Topaz was similar to that at Emerald and Pear lakes. The years from 1987 through 1992 were dry and deposition ranged from about 500 mm to 700 mm; the wet winter of 1993 deposited over 1200 mm of SWE (Figure II-13).

Precipitation in high elevation catchments of the Sierra Nevada occurs primarily during the months of December through April. From 80 to over 90% of annual water deposition is in the form of snow. In wet years, snow can account for greater than 95% of annual precipitation. During the period of study, drought conditions prevailed in California. Annual snow deposition at our catchments was typically 500 to 700 mm of

SWE during dry years and from 1200 to 2000 mm for wet winters such as 1993. During 10 years of study at Emerald Lake, there were 6 dry winters, 2 with near-normal precipitation (1985 and 1991) and two wet winters (1986 and 1993). The mean deposition of snow at Emerald Lake during the past decade was about 1100 mm, an amount that was approached only once during this period. Similarly, non-winter precipitation varies considerably. The summer season can have frequent afternoon thunderstorms (1992) or can be almost completely rainless (1993). Large spring and autumn storms occur in some years (e.g., 1987, 1993, 1994), but frequently these periods have little precipitation.

2.3.2. Streamflow

At Crystal Lake stream runoff is highly seasonal and is dominated by snowmelt runoff (Figures II-14 and II-15). During autumn and winter the outlet stream was usually dry, flowing only during large autumn storm or when winter snowfall displaced lake-water out of the catchment. These displacement events were more common and larger during wet winters.

In the five years of study, snowmelt usually began in mid- to late April. Because of a deeper snowpack and cool spring weather, snowmelt began in May during 1991. In all years the majority of snowmelt runoff took place during the months of May, June and July. The month with the greatest runoff was usually June, but peak flow occurred in May during dry years with warm springs such as 1992. In water year 1993 peak discharge was measured in the month of July. Overall, peak daily-discharge ranged from 10,000 m^3 d^{-1} in 1992 to 20,000-25,000 m^3 d^{-1} in other years. Annual variability in peak monthly flow was large and ranged from 200,000 m^3 per month in 1992 and 1994 to 400,000 m^3 per month in 1993.

The flow-duration curve for Crystal Lake and frequency histogram of daily runoff indicates that the outflow from Crystal Lake was usually dry (flows less than 0.01 mm of runoff being indistinguishable from zero) and the snowmelt season short. Here and in other parts of this report streamflow is expressed as the depth of water in millimeters per unit catchment area. The flow at the 50th percentile was less than 0.3 mm d^{-1} and peak runoff-rates were near 20 mm d^{-1} (Figure II-16). Flow-duration curves are discussed in more detail in Section 2.3.2.1..

Discharge from the Emerald Lake watershed had many of the same characteristics as the outflow from Crystal Lake. The outflow from the lake was dry following snowmelt runoff in drought years, but modest flows persisted when the previous snowpack was large (Figures II-17 and II-18). Autumn rain and snow also kept the outlet flowing. During winter, flow was small and was composed primarily of displaced lake-water from large snowstorms. Snowmelt began, in all years, in late March or early April. Daily runoff gradually increased until it peaked in early June. However in dry years like 1992, peak daily runoff occurred in May. The shape of the snowmelt hydrograph was punctuated by periods of low discharge caused by spring snowstorms that reduced air temperatures and lowered the rate of snowmelt for several days (Figure II-18).

From 1983 through 1994, peak snowmelt runoff from the Emerald Lake basin ranged from ca. 300,000 m^3 per month during drought years to over 600,000 m^3 per month in the wet years of 1986 and 1993. Peak daily discharge during snowmelt varied from about 17,000 m^3 d^{-1} in 1992 to over 33,000 m^3 d^{-1} in 1993. During other years, daily discharge peaked near 20,000 m^3 d^{-1}. Dry channel conditions were less common at Emerald Lake then at Crystal Lake. The flow duration curve and runoff histogram indicate that low to modest flows of 0.1 to 5 mm of daily runoff were most common. Peak runoff was about 30 mm d^{-1} and flow at the 50th percentile was equivalent to 0.6 mm of daily runoff (Figure II-19).

At Lost Lake, streamflow was largely confined to the 3 or 4 snowmelt months each year (Figures II-20 and II-21). Beginning in late summer and continuing through winter, the outflow was usually dry; it flowed only during large rain or snow storms in October or November or after large winter snowstorms forced lake-water into the outlet (these storms are evident in Figure II-21). Snowmelt began in April, earlier in the month during dry years, later in the month when the pack was large. Peak monthly discharge occurred during May in water years 1992 and 1994, in June in 1990 and 1991 and during July in 1993. Cold weather in June 1993 resulted in monthly runoff that was less than in May of that year. Peak daily discharge in 1990 and 1991 was 5,000 to 7,000 m^3 d^{-1}, respectively and occurred in early June. Water year 1993 was quite different. In 1993, peak flows of approximately 10,000 m^3 d^{-1} occurred during three months: May, June and July with the majority of high-flows confined to early July (Figure II-21). Spikes in outflow during 1993 and 1994 were not associated with rain events, but are probably due to the uniformity of the catchment, e.g., low relief, small area, with largely the same aspect and elevation. This uniformity may allow snowmelt to respond more rapidly to meteorologic conditions. Other basins with a wider range of terrain and greater relief, would be less responsive to short-term (hours to days) changes in weather.

At Lost Lake, high daily flows translated into the greatest daily runoff measured during the study (Figure II-22). Peak rates reached 50 mm d^{-1} in 1993. However, on an annual basis, low flows were most common at Lost Lake as evidenced by the flow-duration curve (0.1 to 1 mm per day) (Figure II-22). Runoff at the 50th percentile was approximately 0.5 mm d^{-1}.

Despite draining an area more than 10 times larger than the Emerald Lake watershed (Table II-8), the patterns in streamflow at the Marble Fork station were similar to the other catchments in the Tokopah Valley. Groundwater and shallower subsurface discharge provide much of the river-flow in the Tokopah Valley from late summer through the winter (Figures II-23 and II-24). Base flow is on the order of 500 to 1000 m^3 d^{-1}, but can drop to less than 100 m^3 d^{-1} when the previous snowpack was small and there is little autumn rain or snow (1994). Since the catchment is large, high streamflow was measured at the station. During snowmelt 1993, peak monthly flow was estimated to be ca. 9 million m^3 and a little over 5 million m^3 per month in the drought year of 1994. Peak daily discharge occurred in mid June in 1993 and in early April in 1994. A characteristic of the hydrographs for both years is that high flows are sustained for longer periods of time compared with the smaller catchments. Flows of over 350,000 m^3 d^{-1} were measured during most of May and June in 1993. Likewise, high flows were recorded during much of April and most of May in 1994. The hydrographs for both years show the influence of transient cold spells on runoff. In contrast to the smaller basins, the recession of snowmelt flow occurs earlier and is most likely caused by a higher percentage of south-facing slopes in the Tokopah Valley compared to the Emerald and Pear Lake basins. For example, in early June 1994, discharge out of the Emerald Lake basin was peaking while runoff at the Marble Fork station was nearing base-flow levels. The flow-duration curve at Marble Fork station had a shape similar to those for the smaller basins (Figure II-25). Peak daily runoff was similar to that measured at Emerald Lake, 25 mm d^{-1} and the runoff-histogram indicates that runoff in the range of 1 to 5 mm d^{-1} is most common. Runoff at the 50^{th} was ~1 mm d^{-1}.

Outflow characteristics at Pear Lake were similar to other catchments. After low to zero flows during the autumn and winter, snowmelt usually began in April (Figure II-26). Peak daily discharge was recorded in early June during drought years (1990 and 1992) and in early July in normal to wet years (1991 and 1993) (Figure II-27). Flows ranged from 30,000 to 50,000 m^3 d^{-1}. The pattern in monthly discharge was similar to that at Emerald Lake; peak monthly flow occurred in June during 1991 and 1994 and during May in 1992. In contrast, monthly flow peaked in July during 1993, one month earlier than at Emerald. Flow in 1991 was similar for the months of May and June. Overall, runoff was slightly delayed at Pear in comparison to Emerald. During the years with complete records, peak monthly runoff was typically in the range of 250,000 to 400,000 m^3 and reached nearly 700,000 m^3 in July 1993. The flow-duration curve was similar to those previously discussed (Figure II-28). Maximum runoff rates were near 30 mm d^{-1} with a 50^{th} percentile flow of approximately 0.5 mm d^{-1}. The outflow to the basin would often go dry in late summer following a small snowpack. The most frequently measured runoff rates were in the range of 1 mm d^{-1}.

Outflow at Ruby Lake was distinct from the other basins in several ways. Of the seven lake basins, Ruby was the only one where the outflow ran year round (Figure II-29). Autumn and winter streamflow at Ruby was supplied by drainage from soil and groundwater reservoirs and periodic lake-water displacement caused by heavy snowfalls. Owing to the high elevation of the catchment, winter snowmelt was negligible. The snowpack in the Ruby Lake basin typically began to melt in May, one month later than at the other catchments (Figure II-30). Peak monthly flow occurred in June following the dry winters of 1992 and 1994. In water years 1990, 1991 and 1993, July had the greatest discharge. It is remarkable that in 1993 monthly streamflow for August was nearly the same as the peak snowmelt flow in 1990 and 1991, and the flow measured in September 1993 was only slightly less than the peak monthly discharge in 1992 and 1994. At Ruby, peak runoff was consistent from year to year, ranging from a low of about 550,000 m^3 in 1992 to a high of only 1,000,000 m^3 in the month of July 1993. This range of flows is smaller than the 2 to 3 fold difference in peak monthly discharge observed at the other watersheds.

Appreciable snowmelt at Ruby would often last until early autumn. For example, in 1993, snowmelt remained high well into October and decreased with the advent of colder weather and not because of a lack of snow. During snowmelt, daily flows reached a maximum of 30,000 to 50,000 m^3 d^{-1} with the highest flows occurring in early July except in 1992 when daily flow peaked about a month earlier. Streamflow expressed as mm of runoff also sets the Ruby Lake basin apart from the other sites (Figure II-31). Peak daily runoff was less than 12 mm d^{-1}; less than half the peak runoff measured at any other catchment. The flow-duration curve for Ruby Lake is uncharacteristically flat for Sierran basins indicating that relatively high outflow is more common. The flow histogram shows that runoff of ca. of 1 mm d^{-1} is most frequently encountered and runoff at the 50^{th} percentile was about 0.6 mm d^{-1}. These results show that snowmelt runoff in the Ruby Lake basin is attenuated relative to the other Sierra watersheds in this study. Factors such as the high altitude of the Ruby catchment or the large capacity of the lake may partially explain the difference. It is also likely that a large percentage of snowmelt recharges a substantial groundwater reservoir and infiltrates into soils and tallus fields to be slowly released later in the year.

Persistence of streamflow during periods without snowmelt (e.g., lack of snow or cold temperatures) is evidence of a significant groundwater significant component in the Spuller Lake watershed (Figure II-32). Snowmelt runoff usually begins in mid to late April, a few weeks later than at most sites (Figure II-33). During 1991, snowmelt did not start until early May owing to large late-season storms and cool spring weather. Following the dry winter of 1992, peak daily flows were measured in late May, six weeks earlier than in the other four years of study. Discharge in the range of 17,000 to 24,000 m^3 d^{-1} was typical for peak streamflow during snowmelt. In 1992 peak monthly discharge occurred during May in contrast to June for most other years and July in water year 1993 (Figure II-32). Monthly peak runoff varied from about 200,000 m^3 to 350,000 m^3 in low-snow years and was more than 550,000 m^3 in 1993. Snowmelt runoff typically receded during the summer, reaching baseflow levels (ca. 100-300 m^3 d^{-1}) by late August. Runoff at the 50^{th} percentile was 0.3 mm d^{-1}, and the daily runoff histogram shows that low to modest flows predominate (Figure II-34).

Outflow at Topaz Lake is highly seasonal and was confined primarily to the months of April through July. In most years the outflow was dry throughout the autumn and winter and flowed only during large rain storms or after snow-storms displaced lake-water (Figures II-35 and II-36). Snowmelt began earlier at Topaz than other sites, starting in early to mid April. Peak daily flows ranged from about 20,000 m^3 d^{-1} in 1992 to nearly 50,000 m^3 d^{-1} in 1993, and the month when these peaks were recorded ranged from mid-May (1990 and 1992) to mid or late June (1991 and 1993). The recession of melt proceeds faster at Topaz than at most sites and the outlet usually dries by mid-July; although snowmelt runoff ended in late August during the peak year of 1993. The early initiation and termination of melt at Topaz Lake is largely due to the low relief and high percentage of south-facing slopes in the basin where snowmelt tends to occur sooner and progress most rapidly. Peak monthly discharge occurred in May in most years, and in June following the wetter winters of 1991 and 1993 (Figure II-35). Monthly flow at peak snowmelt ranged from a low of about 300,000 m^3 in water years 1990 and 1994 to a high of nearly 900,000 m^3 in June 1993. Peak daily runoff at the Topaz Lake basin was slightly less than 30 mm d^{-1}, similar to peaks measured at Emerald and Pear and the Tokopah Valley as a whole (Figure II-36). The flow-duration curve at Topaz is relatively steep, indicating a preponderance of low flows (Figure II-37). Flow at the 50^{th} percentile was less than 0.3 mm d^{-1} and the flow-histogram for indicates that low to zero flows dominate the annual hydrograph (Figure II-37).

2.3.2.1. Comparisons of Flow-Duration Curves

Flow-duration curves (F-D curves) are plots of daily runoff (i.e., outflow discharge per unit catchment area. Y-axis) versus exceedence percentage (X-axis). They show the frequency with which daily runoff values are equaled or exceeded. For example, at Crystal Lake, watershed runoff of 1 mm per day was equaled or exceeded approximately 10% of the year (Figure II-16). F-D curves provide information on the hydrologic conditions in a watersheds and serve as a means of comparing runoff processes among the catchments.

The F-D curves take the form of natural logarithmic functions (Figure II-16). The slope and intercept of the curves provide information on important characteristics of annual streamflow. The Y-intercept represents the peak, daily runoff from a catchments. The slope of the F-D curve is an index of the variability or flashiness of runoff from a catchment. Slopes nearer zero (i.e., less negative) are indicative of catchments with low runoff variability while more negative slopes indicate watersheds with high runoff variability (Table II-9). Watershed characteristics such as slope, aspect, area and groundwater storage and release, influence runoff patterns and therefore the flow-duration curve for a catchment. In general, catchments with larger groundwater storage will have lower peak runoff and flow-duration curves with slope nearer zero (less flashy) compared with watersheds with little groundwater capacity (Peters and Murdoch 1985).

The slope and intercept for best fit, flow-duration curves are presented in Table II-9. A log-log plot rather than a semi-log plot is used to aid interpretation at low runoff. The equations take the form of:

$$Y = a + b(\ln X) \qquad (7)$$

where:

Y = daily runoff in millimeters,
X = exceedence percentage (percent of time flow was equaled or exceeded),
a = is the Y intercept (i.e., the highest daily runoff recorded), and
b = is the slope of the best-fit line.

With few exceptions the slopes and intercepts of the F-D curves were similar among the catchments. Peak daily runoff for most watersheds was near 20 mm da^{-1} with higher rates at Lost Lake (33.6 mm da^{-1}) and lower rates at Ruby and Crystal lakes (8.5 and 12.0 mm da^{-1}, respectively) (Table II-9). Annual runoff variability was also similar among the catchments (Table II-9). Most sites had flow-duration slopes of > -5 mm da^{-1} exceedence $\%^{-1}$. The catchments with slopes nearest zero were Crystal and Ruby Lake watersheds (-3.2 and -1.8 mm da^{-1} exceedence $\%^{-1}$, respectively); those with the most negative slopes were Topaz and Lost (-5.4 and -10.7 mm da^{-1} exceedence $\%^{-1}$, respectively).

Several conclusions can be drawn from the F-D analysis. First, hydrologic conditions are, for the most part, similar among the watersheds despite considerable variability in basin size, geographic location and morphology. The catchments exhibited large annual variations in runoff, and, based on the flow-duration curves do not have appreciable groundwater storage with the exception of the Ruby Lake basin. At Crystal, water is lost from the catchment via subsurface flow, resulting in erroneously low peak runoff and less variable flow since the outflow is normally dry. Groundwater flows at Spuller comprise a small fraction of annual discharge and are not evident from the F-D curve.

F-D curve parameters indicate that the Ruby and Lost Lake basins are the most hydrologically distinct of the eight study catchments. Snowmelt at Ruby Lake is attenuated and lengthened because the basin is large, at high elevation and there is sizable groundwater storage and release. In contrast, the Lost Lake catchment is small, lies at a lower elevation, has little groundwater storage capacity therefore runoff responds rapidly to meteorological conditions and tends to be more flashy.

2.3.2.2. Variability of Streamflow

Interannual variability in the timing and magnitude of runoff was a conspicuous feature of streamflow in these Sierran catchments. However, basins in the same geographic area and at similar elevation had similar runoff hydrographs during most years.

Figures II-38 through II-42 show monthly snowmelt runoff for water years 1990 to 1994 for lakes in similar regions i.e., eastern and western slopes of the Sierra Nevada).

Water year 1990 had light snowfall and a modest amount of non-winter precipitation. In eastern Sierra catchments (Lost, Spuller, Ruby and Crystal), snowmelt began in April, but there were large differences in the size and timing of peak runoff among them. Snowmelt proceeded most rapidly at Lost Lake and was completed by the end of June (Figure II-38). At the other extreme, snowmelt was gradual at Ruby Lake with peak runoff in July. At Spuller Lake the majority of runoff was confined to the months of June and July; at Crystal Lake runoff finished in early July. The highest monthly runoff was measured at Lost and Spuller lakes (ca. 280 mm), about twice as large as those at Crystal and Ruby Lake (ca. 150 mm). Melt rates were high at Lost Lake for a variety of reasons. The lower basin elevation, higher spring air temperatures, high SWE (due to blown-in snow), small watershed size and easterly exposure probably caused the snowpack to melt earlier and at a greater rate. Similarly, high rates of snowmelt at Spuller may be caused by the relatively small size of the catchment and its moderate relief and southeasterly aspect.

Snowmelt runoff during water year 1990 in western Sierra catchments was more uniform owing to their geographic proximity. At Emerald, Pear and Topaz melt began in March with peak runoff occurring in May at Topaz Lake and in June at Emerald and Pear, (Figure II-38). Runoff at Topaz Lake was accelerated, compared to the other Tokopah Valley sites, with flow decreasing in June due to a lack of remaining snow. Peak runoff rates in 1990 ranged from 175 to 200 mm per month.

Winter snowfall during water year 1991 was almost completely confined to the month of March. Snow surveys were conducted on February 26, 1991 at Emerald and Topaz and the average depth of snow was between 50 and 60 cm; a large percentage of the catchments were snow-free areas and distributed SWE was only ~100 mm. In March, a series of powerful Pacific storms dropped several meters of snow. By the date of the maximum accumulation survey on April 8, SWE had increased to 1000 mm in the Emerald Lake basin. Similar results were measured at Topaz Lake and the remaining study sites. The March storms, dubbed the "March Miracle", saved the state of California from experiencing its worst drought since 1976 and total precipitation for 1991 approached 'average conditions'. As a consequence of the "late" snowpack and cool springtime weather, snowmelt at all sites was delayed and continued later into the water year. In the eastern Sierra the snowpack did not begin to melt until the month of May. Snowmelt was similar to 1990 with high runoff rates at Lost and Spuller and lower rates at Crystal and Ruby (Figure II-39). Peak monthly runoff increased by about 50% over 1990 levels at the

Lost and Spuller lake basins (400 - 475 mm per month), but was only slightly greater at Crystal and Ruby (ca. 200 mm per month).

As in the eastern Sierra, appreciable snowmelt did not occur in the Tokopah Valley until well into May during 1991 (Figure II-39). Peak runoff occurred in June at all three catchments. At Topaz and Pear, peak monthly runoff was greater than in 1990, 250 to 300 mm. However, peak runoff at Emerald Lake was much greater, with rates twice as high as in 1990 (ca. 400 mm).

Total snowfall in water year 1992 was similar to 1990. In contrast to the dry winter, frequent late summer rains were measured throughout the Sierra Nevada. The yearly monsoonal flow of moisture that typically infiltrates the southwestern United States in the late summer California in 1992, causing many afternoon thunderstorms in the Sierra Nevada during August and September. The combination of a shallow snowpack and warm spring weather caused snowmelt runoff to begin and finish earlier than in other years. In the eastern Sierra snowmelt began in April and peaked during May at Crystal, Spuller and Lost lakes, with peak monthly discharge at Ruby Lake measured in June (Figure II-40). By late summer the outflows were dry at Lost and Crystal and streamflow at Ruby and Spuller was near baseflow levels.

For basins in the western Sierra, the initiation and end of snowmelt in water year 1992 was about 1 month earlier than in other years. Peak monthly discharge was measured in May in all catchments in the Tokopah Valley (Figure II-40). Runoff at Emerald Lake was about half of the amount measured in 1991 and similar to monthly runoff at Pear and Topaz. Snowmelt receded rapidly in June with the steepest decline measured at Topaz Lake. For water years 1991 and 1992, the rank of these lakes in terms of their peak monthly runoff was: Emerald > Topaz > Pear.

The drought that had gripped California since 1987 finally ended during the winter of 1992-93 (water year 1993). Snowfall was 2 to 3 times greater than the annual average of the drought years. In the eastern Sierra, snowmelt began in May and peak monthly runoff occurred in July at all four sites (Figure II-41). Peak flows at Lost and Spuller lakes were twice as large as those measured in 1990 through 1992 and ranged from 500 mm per month at Spuller to nearly 1000 mm per month at Topaz. Increases at Ruby and Crystal were smaller, approximately 150% greater than the peak flows of previous years. Another difference in the runoff pattern of 1993 was the relatively long duration of high flows at Ruby and Crystal. At Ruby Lake, monthly runoff was >100 mm during the months of June through September. Runoff at Crystal Lake was at modest to high levels during May through August and the outflow did not dry until October.

In the Tokopah Valley, snowmelt began in April during 1993 and progressed rapidly during the month of May (Figure II-41). Peak monthly runoff occurred during May at the Marble Fork station, in June at Emerald and Topaz lakes and in July at Pear Lake. Peak monthly runoff was similar among the four sites, ranging from 400 to 450 mm; an amount 50 to 100% greater than measured in previous years. A lengthening of the melt period similar to that at Ruby Lake, was also found in the Tokopah Valley. Modest to high flows were sustained for a period of three months. The recession of snowmelt occurred earliest at the Marble Fork station (June) and then at Topaz (July); outflow at Topaz continued until early September. Snowmelt proceeds more rapidly in these basins because of a lower percentage of north-facing slopes which hold snow well into the summer.

Drought conditions returned to California in water year 1994. Winter snowfall was low, but large storms in April and May brought the yearly precipitation up to the levels measured in water years 1990 and 1992. On the eastern slope of the range snowmelt began in April and peaked during May (Lost Lake) and June (Figure II-42). Because of warm weather, melt proceeded rapidly at Lost Lake and the peak monthly runoff (650 mm) was high considering the light snowpack. At the remaining sites, monthly runoff was about half of the levels measured in 1993, but similar to peak monthly rates in 1990 and 1992. By early August the outlets to Crystal and Lost lakes were dry and flow was at base levels at Ruby and Spuller.

Two snowmelt patterns were evident in the Tokopah Valley during water year 1994. The first, early melt followed by rapid recession, was observed at the Marble Fork station and Topaz Lake. At these sites, melt peaked in May and completed by July; the outflow to Topaz was dry in July while a very small amount of discharge continued into the winter at Marble Fork. At Emerald and Pear, runoff peaked in June and then declined rapidly with both channels dry by early September. The range of monthly peak runoff was greater in 1994 than in 1993, varying from 150 mm at Topaz Lake to 300 mm at Emerald Lake. These values were similar to levels measured in 1990 and 1992 and less than half of the 1993 rates (Figure II-42).

2.3.3. Water Balances

Using measurements of precipitation, outflow discharge and estimates of evaporation from the eight study sites, water balances were calculated for 33 water years. The snow component in the balance combines SWE from snow-surveys with other spring snow. Rain is the sum of precipitation that fell as rain in the spring and summer and as either rain or snow in the autumn (see Section 2.2.1.). The water balance residual is computed as the difference between measured inputs and losses. As such, it indicates unmeasured components (e.g., changes in groundwater storage, snow that carries over into the next water year etc..) or water balance errors. If inputs exceeded losses the residual is positive, if losses exceeded inputs the sign is negative. An accurate water balance should have a small residual based on the uncertainties and systematic errors in the computation. In this study, a negative residual is expected because of small, systematic underestimates of water inputs from autumn and spring storms and midwinter snowmelt. Discharge calculations based on dilution-based rating curves show a systematic overestimate of losses which contributes to a negative residual term in the water balance.

In the figures and tables, losses of water are given a negative sign (i.e., outlet streamflow and evaporation) and inputs are positive sign (i.e., snowfall and rain). The annual water balances are presented in the form of histograms with accompanying data tables, expressing the measured fluxes in mm of water (i.e., input or losses per unit catchment area). The histograms show the fluxes as percentages of either inputs or outputs and facilitate comparisons of the water-balance components between wet and dry years.

At Crystal Lake the largest components in the water balance were evaporation and snowfall (Figure II-43). Water from snow comprised from 80% to 99% of annual input.

Lower percentages were measured in years with dry winters (1990, 1992) and the highest percentages in years with wet winters (1991 and 1993). Evaporation was the greatest loss in 1990, 1991 and 1992, but streamflow exceeded evaporation in 1993. At Crystal evaporative losses expressed as a percentage of precipitation were 65% in 1990, 70% in 1991, 45% in 1992 and 20% in 1993. The water balance residuals were small (less than 10% of losses) and in 1990 and 1991 (+8 and -66 mm respectively), but were much larger in 1992 and 1993 (+270 and +589 mm respectively) when gauging accuracy improved. During these latter years the residual represented ~20% of inputs. The large residuals and the lower percentage of outflow discharge in the water balance (compared to the other catchments) were caused by subsurface flows from Crystal Lake. Unmeasured groundwater leakage caused a systematic underestimate of outflow losses and a concurrent increase in the percentage of water lost via evaporation. Several perennial springs located down slope of the catchment provide evidence of groundwater loss. The shallower slope of the flow-duration curve for Crystal (Table II-9) also supports this finding. In addition, substantial groundwater flow has been measured by others in the vicinity of the catchment (Overturf 1991) and the springs below Crystal Lake have flow throughout the summer and autumn when the outlet to Crystal Lake is dry. The Crystal Lake basin and the surrounding area are underlain by volcanic ash and debris conducive to subsurface flows. The fact that residuals in 1990 and 1991 were not large is explained by systematic overestimates of outflow discharge. Rating curves for these years were based on the less accurate slug-injection method, and the transducers was not as well placed as in later years. Streamflow measurements were improved in 1992 and 1993.

The Emerald Lake watershed can be considered a "tight" catchment (i.e., no subsurface loss of water) and its water balance is dominated by snow deposition and outflow discharge (Figure II-44). At Emerald, snowfall comprised 75% to 95% of water input with the highest percentages measured in the two wettest winters: 1991 and 1993. During two of the drought years, 1990 and 1992, non-winter precipitation accounted for more than 20% of water inputs. Outflow exceeded evaporation in all water year and outflow discharge comprised a larger percentage of losses during wet years (1991 and 1993). On an annual basis, evaporation (expressed as a percentage of precipitation) was 36% in 1990, 29% in 1991, 48% in 1992, 12% in 1993 and 53% in 1994. The residual in water years 1990, 1991 and 1992 was negative (as expected) and represented 10% to 17% of losses. In water year 1993, the residual was positive and represented almost 20% of inputs. The change in sign of the residual in 1993 is due to the fact that a significant percentage of the snowpack did not melt by the end of the water year (September 30). Left-over snow was carried over and melted in 1994, explaining the relatively large, negative residual (-22%, i.e., too much outflow) measured in this year.

At Lost Lake, the primary components in the water balances were snowfall and outflow. Because of deep snowpacks, snow represented about 90% of annual water input, high compared to the other sites (Figure II-45). Outflow at Lost Lake exceeded evaporation by a factor of ~3 in the drought years of 1990 and 1992, and outflow was more than 8 times greater than evaporation in water year 1993. Evaporation represented 25% of precipitation in 1990, 28% in 1991, 37% in 1992 and 9% in 1993. Since there was no weather station in the vicinity of Lost Lake, evaporation in the catchment could not be directly measured. Instead, evaporation from Emerald Lake was used. Despite the large geographical separation of these sites and the altitude difference between them, evaporation rates may not be that different at Lost and Emerald lakes. Factors such as increased latitude versus lower elevation, and greater input of solar radiation versus faster recession of snow-covered area may have balanced each other. Calculated evaporation rates for the other catchments showed a reasonable amount of similarity, with typical differences around ± 25%, so this substitution should not have introduced substantial error into the water balances at Lost Lake. In addition, an analysis of evaporation using chloride evapoconcentration showed similar evaporation rates for the Emerald and Lost lake catchments (see Chapter 4).

Water balances were computed for two years for the Tokopah Valley (i.e., upper Marble fork of the Kaweah River). The gauging station measures runoff from the Tokopah Valley and includes the outflow from Emerald, Pear and Topaz lakes. Because the gauging station was not operational during most of water year 1993, flow was estimated from a regression between daily discharge in 1994 at this station and Emerald Lake. Two regressions equations were used, one for the rising limb of the snowmelt hydrograph ($r^2 = 0.94$) and the other for the falling limb ($r^2 = 0.88$). As such, the Marble Fork data from 1993 should be used with caution since 1993 and 1994 were quite different. To improve the 1993 estimates, we plan to check the regression using data from 1995 - 1997. Another caveat regarding the water balance for 1993 is that mean SWE for the Marble Fork drainage was estimated from a fairly limited survey of the basin; depth measurements were confined to the Topaz, Pear, Emerald lake basins and the M-site catchments (Sierra Nevada Episodes Project). In 1994 a large-scale survey was made in the Tokopah Valley. Marble Fork rain was assumed to equal rain measured at Emerald Lake during both years.

In the Marble Fork water balances, snowfall and outflow accounted for most of the fluxes of water into and out of the basin (Figure II-46). Snow constituted 92% of precipitation in 1993 and 93% in 1994. Outflow was over 6 times greater than evaporation in water year 1993, but only 2.5 times greater during 1994. Evaporation in 1993 accounted for 12% of water input in 1993 and 38% in 1994. Snowmelt during water year 1993 was incomplete and snow was carried over into the following water year, explaining the positive residual in water year 1993 and the rather large negative residual in 1994 (ca. 21%). However, the cumulative water balance for 1993-1994 has a residual of -238 mm which suggests that streamflow was overestimated during 1993 and snow carry-over was greater than indicated by the 1993 residual.

The major components in the water cycle at Pear Lake were snow deposition and streamflow (Figure II-47). Snowfall in this basin comprised about 90% of inputs in 1991 and 1993 and ca. 80% of input water years 1990 and 1992. During drought years (1990 and 1992), streamflow exceeded evaporation by less than a factor of two. Snow deposition had a strong effect on the percentage of water loss by evaporation. Evaporation occurs mainly during late spring and summer, when free water and wet soils are abundant. Direct evaporation from the snowpack (Chapter Four) during snowmelt can be considered negligible. Therefore, in a heavy snow year, not only are evaporative losses a much smaller percentage of water inputs, but longer snowcover reduces the absolute evaporative loss by limiting the time and area where high evaporation can occur. In 1992 (the driest winter), evaporative losses accounted for 50% of the input of water to the Pear

Lake Basin. In contrast, evaporation was only 13% of inputs in 1993 (the wettest winter). The residual term in the water budgets at Pear Lake was positive in 3 out of 4 years; it was negative only during 1992. As a percentage of inputs or losses the residuals were on the order of 10% to 15%.

Storage and release of groundwater had a large effect on hydrology in the Ruby Lake basin, but the major water balance components were snow and outflow (Figure II-48). Snow deposition accounted for 80% to 97% of precipitation, with the highest percentage measured during water year 1993. Evaporation was a large loss in the water budgets, comprising 25% to 40% of water losses. During water years 1990, 1992 and 1994 evaporation accounted for about 35% to 40% of the inputs of water. Evaporative losses were greater in 1991 (~46% of inputs) than in 1993 (~16%) owing to persistent snow-cover. The residuals for the water budgets at Ruby were small except for an expected positive residual (ca. 35% of input) in 1993 caused by unmelted snow that carried over into the next water year. During other years the residual in the annual budget ranged from <1% to 12% of inputs. The small residuals indicate that, despite groundwater inputs to the lake, the watershed as a whole is tight and does not loose water via subsurface flow.

At the Spuller Lake basin, snow accounted for a high percentage of water input, ranging from ~80% (1992) to greater than 97% (1993) of annual precipitation (Figure II-49). Outflow discharge was the largest loss term; during most years, evaporation was typically only half as large as outflow and at the extreme represented only 13% of water output during 1993. Ranking the years by the percentage of inputs lost by evaporation the order would be 1990: 40%, 1991: 41%, 1992: 33%, 1994: 25% and 1993: 10%. Evaporation decreased in magnitude and as a percentage of total losses when the snowpack was deep and persistent (e.g., 1993). The residual term was < 15% of outputs during 1990 and 1991. Small (<10% of losses) residuals occurred in water years 1992 and 1994 and the expected, positive residual was measured in 1993. Positive residuals in 1992 and 1994 may be due, in part, to a slight underestimate of discharge caused by leakage from the Spuller Lake weir. Groundwater inputs to the lake were small on an annual basis, but did maintain low outflow between snowmelt runoff periods.

The water balances for the Topaz Lake basin were surprisingly good given the difficulties in gauging the outflow stream (Figure II-50). As was typical of the other study catchments, the major input to the Topaz watershed was snow and the major loss, outflow discharge. Snowfall comprised ~75% to >90% basin precipitation, slightly less than at the other catchments due to lower snow deposition at this site. Because of relatively shallow snowpacks and faster recession of snow covered area, evaporation comprised a larger percentage of water loss at Topaz than at most other catchments. Evaporation accounted for 37% of total precipitation in 1990, 33% in 1991, 43% in 1992 and 19% in 1993. The water balance residual at Topaz was between 10 to 18% of inputs in 1990 and 1991 and less than 5% of inputs in 1992 and 1993. The 1993 snowpack completely melted at Topaz so there was no large, positive residual for this water balance.

2.4. Conclusions

The hydrology of high elevation catchments in the Sierra Nevada is dominated by the accumulation and melting of the winter snowpack. The majority of catchment outflow occurs during the annual snowmelt period which begins as early as late March following dry winters in the western Sierra, but may not start until early May in the eastern Sierra Nevada when snowpacks are deep. Peak runoff occurred in early to mid June when winter snowfall was light and during late June and early July in wet years (e.g., 1993). At some catchments, peak outflow discharge following a wet winter was much greater than in dry years (e.g., Lost and Topaz lakes) while in others the range of peak flows was relatively small (e.g., Ruby and Crystal lakes).

The percentage of water lost via outflow was also related to the size of the winter snowpack and was greatest following winters with abundant snowfall. In contrast, evaporative losses decreased in percentage when snowpacks were deep owing to the slow recession of snow-cover in the basins. The amount of precipitation to the basins that was lost to evaporation ranged from about 10% in wet years to as great as 50% during drought years. The average loss of water to evaporation for the water balances in this report was, excluding Crystal Lake, ~30%. Overall, non-winter precipitation comprised a small component of the annual water budgets.

Snowmelt from seasonally snow-covered catchments in the Sierra Nevada was often punctuated by periods of low discharge caused by spring snowstorms that cooled air temperatures and lowered the rate of snowmelt for several days at a stretch. Following peak discharge, runoff receded gradually during the summer and autumn. However, groundwater storage and release in the Ruby Lake basin are partly responsible for maintaining year-round outflow. At most catchments, outflow streams went dry by September when snow-cover was gone which indicates that little water is stored in most Sierran watersheds. With the exception of the Crystal Lake basin, the catchments in the study lost little water via subsurface flow and were hydrologically tight. Winter runoff at all catchments was very low. At basins without groundwater inputs, winter streamflow was primarily the result of displacement of lake water by snowfall and, to a lesser extent, from winter snowmelt from south-facing slopes.

The residual term for the water budgets indicated a slight bias toward too much loss and/or too little input. Excluding the positive residuals that were caused by carry over of snow from water year 1993 into water year 1994, 16 out of the 25 water balances had negative residuals. This supports our assumption that the water-balances for this study may have missed small amounts of precipitation and slightly overestimated outflow because of errors introduced by salt-dilution gauging.

2.5. References

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Table II-1. Sources of non-winter precipitation data used in solute and water balances for water years 1990 through 1994. Precipitation gauge location identifies the primary site where non-winter precipitation was measured for each watershed. Precipitation collector location identifies the site where precipitation chemistry for each watershed was determined. Alternate station is a backup gauge used to fill in gaps in the primary rain gauge record caused by instrument malfunction. Source for April, May and November precipitation list the station locations used to estimate precipitation at each watershed during spring and late autumn when the tipping bucket gauges were not operated. The following abbreviations are used:

MLRS - U.S. Forest Service Ranger Station, Mammoth Lakes, California
LMS - Lake Mary store, Mammoth Lakes California
LPRS - U.S. National Park Service Ranger Station, Lodgepole, Sequoia N.P.
SB - Snowboard within watershed
SP - Snowpit within watershed
EML - Emerald Lake

At the two ranger stations and the Lake Mary store, precipitation was measured in a U.S. Forest Service approve rain/snow gauge (Belfort). Eastern Brook Lake and the Carnegie Station are part of the Alpine Deposition Monitoring network operated by UCSB. Eastern Brook Lake is located in the Rock Creek Canyon, approximately 4 km and 220 meters lower than the outlet to Ruby Lake. The Carnegie Station is located about 3 km north of and 140 meters lower than Spuller Lake.

Watershed	Precip. Gauge Location	Precip. Collector Location	Alternate Station for Gauge	Source for April, May, November Precip.
Crystal	Lake outlet	Mammoth Mt.	Mammoth Mt.	MLRS, LMS
Emerald	Lake inlet	Lake inlet	Topaz Lake	SB, SP, LPRS
Lost	Angora Lake	Angora Lake	None	None
Marble Fork	Emerald Lake	Emerald Lake	Topaz Lake	EML, LPRS
Pear	Emerald Lake	Emerald Lake	Topaz Lake	EML, LPRS
Ruby	Lake outlet	Eastern Brook LK.	Mammoth Mt.	MLRS, LMS
Spuller	Lake outlet	Carnegie Station	Mammoth Mt.	MLRS, LMS
Topaz	Lake outlet	Emerald Lake	Emerald Lake	EML, LPRS

Table II-2. Summary of watershed snow surveys conducted at maximum snowpack accumulation during water years 1990 through 1994. Number of Snowpits is the number of pits dug and sampled (for chemistry, density and temperature) during the snow survey. Number of Snow Depths is the total number of depth measurements made with probes during the survey. Number of Federal samples is the number of density and SWE determinations made with a Federal Snow Sampler. Snowpits from adjacent drainages (M1, M2, M3 and Emerald) were used for SWE calculations at Pear Watershed during 1993.

Watershed	Year	Number of Snowpits	Number of Snow Depths	Number of Federal Samples	Snow Survey Date
Crystal	1990	2	478	0	March 28
	1991	2	144	0	April 20
	1992	2	372	0	April 3
	1993	1	202	0	April 13
Emerald	1990	3	280	0	March 19
	1991	3	232	0	April 8
	1992	3	408	0	March 26
	1993	3	238	7	April 7
	1994	2	217	43	March 28-30
Lost	1990	2	224	0	April 5
	1991	2	168	0	April 22
	1992	3	424	0	April 6
	1993	1	42	7	March 30
Pear	1990	2	384	0	March 21
	1991	2	292	0	April 10
	1992	2	300	0	March 25
	1993	0	402	0	April 7
Ruby	1990	2	284	0	March 22
	1991	2	300	0	April 18
	1992	2	408	44	April 4
	1993	3	740	0	April 27
	1994	4	847	15	April 4-7
Spuller	1990	3	344	0	March 26
	1991	2	297	0	April 19
	1992	3	535	0	April 2
	1993	3	258	0	April 15
	1994	1	499	0	April 22
Topaz	1990	2	332	0	March 20
	1991	2	168	0	April 9
	1992	2	440	0	March 24
	1993	2	120	0	April 7
Marble Fork	1993	4	760	7	April 7
	1994	5	1569	88	March 28-30

Table II-3. Estimated error in rain and snow volumes at the study catchments for water years 1990 through 1994. For purposes of the error analysis, non-winter precipitation is divided into three components: spring rain/snow, summer rain and autumn rain/snow. The errors associated with these components were propagated (root sum-square method) to yield the error in non-winter precipitation volume. Errors in winter snow volume was estimated by comparing distance-weighted mean SWE to mean SWE computed by a snow-distribution model (Elder 1995).

Catchment	Spring Rain/Snow	Summer Rain	Autumn Rain/Snow	Non-winter Precipitation	Winter Snow
Crystal	5.0%	5.0%	5.0%	8.7%	5.0%
Emerald	5.0%	5.0%	5.0%	8.7%	5.0%
Lost	7.5%	5.0%	10.0%	13.5%	5.0%
Marble Fork	5.0%	5.0%	5.0%	8.7%	5.0%
Pear	5.0%	5.0%	5.0%	8.7%	5.0%
Ruby	7.5%	5.0%	10.0%	13.5%	5.0%
Spuller	7.5%	5.0%	10.0%	13.5%	5.0%
Topaz	5.0%	5.0%	5.0%	8.7%	5.0%

Table II-4. Comparison of distance-weighted mean SWE and mean SWE computed by a snow distribution model (Elder 1995). Units are meters of SWE. Data used are from the maximum accumulation surveys of 1993 and 1994.

Site/Year	Modeled Mean SWE (m)	Distance-weighted Mean SWE (m)	Ratio Model/Mean
Emerald 1993	2.20	2.18	1.01
Emerald 1994	0.68	0.70	0.97
Ruby 1993	1.45	1.50	0.97
Ruby 1994	0.63	0.56	1.13
Spuller 1993	1.87	1.96	0.95
Spuller 1994	0.84	0.82	1.02
Crystal 1993	1.89	1.75	1.08

Table II-5. Summary of rating curves for water years 1987 through water-year 1994. At the lake basins, readings from the pressure transducers (volts) were used directly in the discharge calculations. At the Marble Fork station, pressure readings were converted to stage readings (via a linear regression with staff gauge readings) before fitting the rating curve. Stage is the depth of flow in the stream in units of cm or ft. The equations take the general form of:

$$Q = 10^{[((\text{Log } V) - B) / M]}$$

where; Q = discharge in $m^3\ s^{-1}$,
V = transducer voltage (or stage),
B = y-intercept of log:log regression, and
M = slope of log:log regression.

N is the number of data points in the rating curve (slug injection salt dilutions or constant injection salt dilutions), r^2 is the coefficient of variation for the log:log regression and Type refers to the full scale range of the pressure transducer (1 or 5 lb. in^2 (psi)). For Emerald and Spuller Lakes the weir equations were used starting in 1991 to calculate discharge (see Table II-6). Beginning in water year 1991 two transducers were deployed in each stream and are referred to as number one or two and shown in parenthesis. The asterisk indicates which transducer's discharge was used in the water and solute balances contained in this report. At Pear Lake, only transducer #2 was operated during water years 1990 through 1994. At Lost Lake, transducer #2 was used to calculate flows only during 1993.

Lake	Water Years	M	B	N	r^2	Type
Crystal	*1987-1988(1)	0.1043	0.6274	42	0.99	1 psi
	*1989-1990(1)	0.1348	0.6609	66	0.92	1 psi
	*1991-1992(1)	0.1348	0.6609	66	0.92	1 psi
	1991-1992(2)	0.1362	0.6997	66	0.96	1 psi
	*1993-1994(1)	0.1407	0.6736	65	0.96	1 psi
	1993-1994(2)	0.1302	0.6924	65	0.96	1 psi
Emerald	*1989-1990(1)	0.2171	0.7100	17	0.94	1 psi
Lost	*1990-1991(1)	0.0982	0.3641	47	0.80	1 psi
	*1992-1994(1)	0.1215	0.4270	64	0.85	1 psi
	*1990-1994(2)	0.1332	0.5532	111	0.75	1 psi
Pear	*1987-1989(1)	0.1348	0.4529	30	0.97	1 psi
	*1990-1992(2)	0.2037	0.6082	83	0.94	1 psi
	*1993(2)	0.2023	0.6235	50	0.98	1 psi
	*1994(2)	0.1200	0.6900	15	0.98	1 psi
Ruby	*1987-1990(1)	0.0542	0.1541	108	0.97	5 psi
	*1991(1)	0.0659	0.1923	36	0.98	5 psi
	1992(1)	0.0626	0.1810	34	0.93	5 psi
	1993-1994(1)	0.0600	0.1776	54	0.92	5 psi
	1991(2)	0.2404	0.6152	36	1.00	1 psi
	*1992(2)	0.1874	0.5537	34	0.97	1 psi
	*1993-1994(2)	0.1703	0.5431	54	0.94	1 psi

Table II-5. Continued.

Lake	Water Years	M	B	N	r^2	Type
Spuller	1990(1)	0.2568	0.6532	51	0.63	1 psi
	1990(2)	0.3462	0.7681	51	0.78	1 psi
Estimated:	*1990(1)	0.1250	0.4600			1 psi
Topaz	*1987-1989(1)	0.0636	0.3013	37	0.98	5 psi
	*1990(1)	0.1025	0.3424	22	0.97	5 psi
	*1991-1993(1)	0.0699	0.3284	45	0.89	5 psi
	1991(2)	0.2164	0.8076	22	0.93	1 psi
	1992-1993(2)	0.2261	0.7562	45	0.88	1 psi
Marble Fork	*1994(1&2)	0.2448	-0.4570	16	0.99	5 psi

Table II-6. Summary of relationships between transducer voltages and stage for weirs at Emerald and Spuller outflows for the period of water years 1991 through 1994. The equations for discharge in the weirs were:

Emerald: 1. Stage < 45.8 cm: $Q = 0.0239\,H^{2.5}$
2. Stage ≥ 45.8 cm: $Q = 0.0239\,H^{2.5} - 0.0239(H-45.8)^{2.5}$

Spuller: 1. For all stages: $Q = 0.0138\,H^{2.5}$

where: Q = discharge in liters per second
H = stage of water in the weir in cm

In the table the slope, intercept and coefficient of determination (r^2) from linear regressions between stage (depth of flow in weir) and transducer voltage are given. The equations take the form of:

$$H = m(V) + b$$

where: H = stage (cm)
V = transducer voltage
m = slope of the equation
b = intercept of equation

The asterisk indicates which transducer's discharge was used in the water and solute balances contained in this report.

Lake	Water Years	M	B	N	r^2	Type
Emerald	*1991-1993(1)	65.04	-102.77	158	0.99	5 psi
	*1994(1)	66.73	-106.32	25	0.99	5 psi
	1991(2)	15.18	-47.43	37	1.00	1 psi
	1992(2)	14.56	-48.50	13	0.94	1 psi
	1993(2)	13.16	-46.77	108	0.85	1 psi
	1994(2)	11.82	-46.31	25	0.96	1 psi
Spuller	*1991-1994(1)	14.13	-38.60	93	0.95	1 psi
	1991-1994(2)	14.50	-40.26	93	0.95	1 psi

Table II-7. Estimated error in annual outflow discharge measurements for the study catchments during water years 1990 through 1994. For purposes of the error analysis, uncertainty in discharge errors for water years 1985, 1986 and 1987 were assumed to be 20%, 10% and 10% respectively (Kattelmann and Elder 1991). The estimates are based, primarily, on comparisons between discharge measurements made with tracers (i.e., slug and constant-injection salt dilutions) and weirs (Emerald and Spuller lakes). Channel morphometry and pressure transducer placement were also used to estimate discharge error.

Year	Crystal	Emerald	Lost	Marble Fork	Pear	Ruby	Spuller	Topaz
1990	15%	10%	20%	-	25%	15%	20%	20%
1991	15%	5%	20%	-	25%	15%	6%	20%
1992	10%	5%	15%	-	15%	10%	6%	15%
1993	10%	5%	15%	20%	15%	10%	6%	15%
1994	10%	5%	15%	15%	15%	10%	6%	15%

Table II-8. Summary of basin and lake characteristics. Basin area is the amount of drainage area above the outflow gauging station. The lake volume to watershed index is the volume of a lake (cubic meters) divided by the area of the lake's drainage basin (square meters). For the Marble Fork, lake volume is the sum of volumes from Emerald, Pear and Topaz Lakes plus an additional 230,000 m^3 estimated lake volume from Aster Lake and other small ponds in the catchment.

Lake/Basin	Basin Area (ha)	Basin Relief (m)	Lake Area (ha)	Outlet Elev. (m)	Lake Max. Depth (m)	Lake Mean Depth (m)	Lake Volume (m^3)	Lake Volume to Watershed Area Index (m^3/m^2)
Crystal	135	293	5.0	2,951	14	6.5	324,000	0.24
Emerald	120	616	2.7	2,800	10	6.0	162,000	0.14
Lost	25	160	0.7	2,475	5.5	1.9	12,500	0.05
Pear	136	471	8.0	2,904	27	7.4	591,000	0.43
Ruby	441	812	12.6	3,390	35	16.4	2,080,000	0.47
Spuller	97	537	2.2	3,131	5.5	1.6	34,700	0.04
Topaz	178	275	5.2	3,218	5.0	1.5	76,900	0.04
Marble Fork of Kaweah River	1,908	872	30	2,621	NA	NA	1,059,000	0.06

Table II-9. Slope, intercept and coefficient of determination (r^2) for best fit line for flow-duration curves (i.e., runoff vs exceedance percentage) for the seven lake basins and the Marble Fork of the Kaweah. Equations take the form of: $Y = a + b(\ln X)$ where a is the intercept and b is the slope.

Watershed	Intercept	Slope	r^2
Crystal	12.0	-3.2	0.98
Emerald	20.3	-4.8	0.95
Lost	33.6	-8.7	0.97
Marble Fork	21.1	-4.5	0.86
Pear	17.4	-4.9	0.97
Ruby	8.5	-1.8	0.96
Spuller	18.9	-4.6	0.93
Topaz	18.6	-5.4	0.98

Figure Captions

Figure II-1. Comparison of discharge measured with tracer (slug and constant-injection salt dilutions) and the weir at the Emerald Lake watershed from 1991 through 1994. The 1:1 line and the best-fit line are shown in the plots. Also shown is the equation of the line of best fit and the standard error of the estimate.

Figure II-2. Time-series of daily and monthly discharge measured by the weir and computed from a rating curve based on dilution-derived discharge at Emerald Lake during water year 1993.

Figure II-3. Comparison daily discharge measured with weirs and daily discharge computed from rating curves based on dilution-derived discharge at Emerald and Spuller lakes during water year 1993. The 1:1 line is shown on the plots.

Figure II-4. Comparison of discharge measured with tracer (slug and constant-injection salt dilutions) and buckets versus the weir at the Spuller Lake watershed from 1991 through 1994. The 1:1 line and the best-fit line are shown in the plots. Also shown is the equation of the line of best fit and the standard error of the estimate.

Figure II-5. Time-series of daily and monthly discharge measured by the weir and computed from a rating curve based on dilution-derived discharge at Spuller Lake during water year 1993.

Figure II-6. Frequency of standard error for replicate dilution-discharge measurements done at constant stage from 1987 through 1994 at the eight study sites. The dilution-discharge measurements include both slug and constant-injections of salt solution. On most occasions 3 to 4 replicates were conducted.

Figure II-7. Annual non-winter and winter precipitation at the Emerald Lake watershed for water years 1985 through 1994. Winter precipitation is expressed as snow water-equivalence (SWE).

Figure II-8. Annual non-winter and winter precipitation at the Crystal Lake watershed for water years 1987 through 1993 Winter precipitation is expressed as snow water-equivalence (SWE).

Figure II-9. Annual non-winter and winter precipitation at the Lost Lake watershed for water years 1990 through 1993. Winter precipitation is expressed as snow water-equivalence (SWE).

Figure II-10. Annual non-winter and winter precipitation at the Pear Lake watershed for water years 1987 through 1993. Winter precipitation is expressed as snow water-equivalence (SWE).

Figure II-11. Annual non-winter and winter precipitation at the Ruby Lake watershed for water years 1987 through 1994. Winter precipitation is expressed as snow water-equivalence (SWE).

Figure II-12. Annual non-winter and winter precipitation at the Spuller Lake watershed for water years 1990 through 1994. Winter precipitation is expressed as snow water-equivalence (SWE).

D curve) indicates the percentage of time daily runoff (i.e., outflow discharge per unit catchment area) equaled or exceeded a given rate. The histogram shows the frequency that daily runoff was at or below the level indicated on the x-axis, e.g., 0.01 represents: runoff $\leq$ 0.01 mm day$^{-1.}$, 5 represents: 1 < runoff $\leq$ 5 mm day^{-1} etc..

Figure II-26. Monthly outflow discharge at the Pear Lake watershed from 1986 through 1994. Top panel shows detail from water years 1990 through 1994.

Figure II-27. Daily outflow discharge at the Pear Lake watershed for water years 1990 and 1994.

Figure II-28. Flow duration curve and runoff-frequency histogram for the Pear Lake outflow from 1986 through 1994. The flow-duration curve (F-D curve) indicates the percentage of time daily runoff (i.e., outflow discharge per unit catchment area) equaled or exceeded a given rate. The histogram shows the frequency that daily runoff was at or below the level indicated on the x-axis, e.g., 0.01 represents: runoff $\leq$ 0.01 mm day$^{-1.}$, 5 represents: 1 < runoff $\leq$ 5 mm day^{-1} etc..

Figure II-29. Monthly outflow discharge at the Ruby Lake watershed from 1986 through 1994. Top panel shows detail from water years 1990 through 1994.

Figure II-30. Daily outflow discharge at the Ruby Lake watershed for water years 1990 and 1994.

Figure II-31. Flow duration curve and runoff-frequency histogram for the Ruby Lake outflow from 1986 through 1994. The flow-duration curve (F-D curve) indicates the percentage of time daily runoff (i.e., outflow discharge per unit catchment area) equaled or exceeded a given rate. The histogram shows the frequency that daily runoff was at or below the level indicated on the x-axis, e.g., 0.01 represents: runoff $\leq$ 0.01 mm day$^{-1.}$, 5 represents: 1 < runoff $\leq$ 5 mm day^{-1} etc..

Figure II-32. Monthly outflow discharge at the Spuller Lake watershed from 1989 through 1994. Top panel shows detail from water years 1990 through 1994.

Figure II-33. Daily outflow discharge at the Spuller Lake watershed for water years 1990 and 1994.

Figure II-34. Flow duration curve and runoff-frequency histogram for the Spuller Lake outflow from 1989 through 1994. The flow-duration curve (F-D curve) indicates the percentage of time daily runoff (i.e., outflow discharge per unit catchment area) equaled or exceeded a given rate. The histogram shows the frequency that daily runoff was at or below the level indicated on the x-axis, e.g., 0.01 represents: runoff $\leq$ 0.01 mm day$^{-1.}$, 5 represents: 1 < runoff $\leq$ 5 mm day^{-1} etc..

Figure II-35. Monthly outflow discharge at the Topaz Lake watershed from 1986 through 1994. Top panel shows detail from water years 1990 through 1994.

Figure II-36. Daily outflow discharge at the Topaz Lake watershed for water years 1990 and 1994.

Figure II-37. Flow duration curve and runoff-frequency histogram for the Topaz Lake outflow from 1986 through 1994. The flow-duration curve (F-D curve) indicates the percentage of time daily runoff (i.e., outflow discharge per unit catchment area) equaled or exceeded a given rate. The histogram shows the frequency that daily runoff was at or below the level indicated on the x-axis, e.g., 0.01 represents: runoff $\leq$ 0.01 mm day^{-1}, 5 represents: 1 < runoff $\leq$ 5 mm day^{-1} etc..

Figure II-38. Monthly runoff (i.e., outflow discharge per unit catchment area) during the snowmelt period of 1990 for catchments in the eastern Sierra Nevada (Crystal, Ruby, Spuller and Lost) and in the western Sierra (Tokopah Valley: Emerald Pear and Topaz).

Figure II-39. Monthly runoff (i.e., outflow discharge per unit catchment area) during the snowmelt period of 1991 for catchments in the eastern Sierra Nevada (Crystal, Ruby, Spuller and Lost) and in the western Sierra (Tokopah Valley: Emerald Pear and Topaz).

Figure II-40. Monthly runoff (i.e., outflow discharge per unit catchment area) during the snowmelt period of 1992 for catchments in the eastern Sierra Nevada (Crystal, Ruby, Spuller and Lost) and in the western Sierra (Tokopah Valley: Emerald Pear and Topaz).

Figure II-41. Monthly runoff (i.e., outflow discharge per unit catchment area) during the snowmelt period of 1993 for catchments in the eastern Sierra Nevada (Crystal, Ruby, Spuller and Lost) and in the western Sierra (Tokopah Valley: Emerald Pear Topaz and the upper Marble Fork of the Kaweah River).

Figure II-42. Monthly runoff (i.e., outflow discharge per unit catchment area) during the snowmelt period of 1994 for catchments in the eastern Sierra Nevada (Crystal, Ruby, Spuller and Lost) and in the western Sierra (Tokopah Valley: Emerald Pear Topaz and the upper Marble Fork of the Kaweah River).

Figure II-43. Annual water balances for the Crystal Lake watershed from water years 1990 through 1993. In the bar graph, individual inputs, losses and residuals are expressed as percentages of total water inputs or total water losses, respectively. Units are mm of runoff per water year (i.e., water-year discharge per unit catchment area).

Figure II-44. Annual water balances for the Emerald Lake watershed from water years 1990 through 1994. In the bar graph, individual inputs, losses and residuals are expressed as percentages of total water inputs or total water losses, respectively. Units are mm of runoff per water year (i.e., water-year discharge per unit catchment area).

Figure II-45. Annual water balances for the Lost Lake watershed from water years 1990 through 1993. In the bar graph, individual inputs, losses and residuals are expressed as percentages of total water inputs or total water losses, respectively. Units are mm of runoff per water year (i.e., water-year discharge per unit catchment area).

Figure II-46. Annual water balances for the upper Marble Fork of the Kaweah River (Tokopah Valley) from water years 1993 and 1994. In the bar graph, individual inputs, losses and residuals are expressed as percentages of total water inputs or total water losses, respectively. Units are mm of runoff per water year (i.e., water-year discharge per unit catchment area).

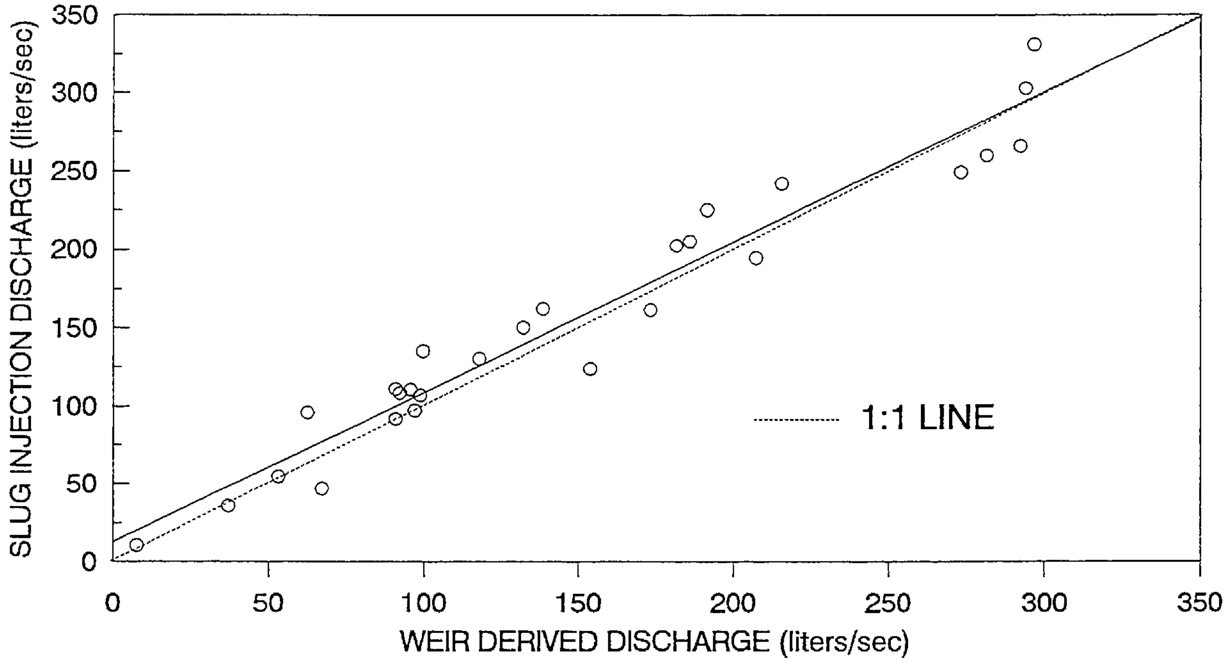
Figure II-47. Annual water balances for the Pear Lake watershed from water years 1990 through 1993. In the bar graph, individual inputs, losses and residuals are expressed as percentages of total water inputs or total water losses, respectively. Units are mm of runoff per water year (i.e., water-year discharge per unit catchment area).

Figure II-48. Annual water balances for the Ruby Lake watershed from water years 1990 through 1994. In the bar graph, individual inputs, losses and residuals are expressed as percentages of total water inputs or total water losses, respectively. Units are mm of runoff per water year (i.e., water-year discharge per unit catchment area).

Figure II-49. Annual water balances for the Spuller Lake watershed from water years 1990 through 1994. In the bar graph, individual inputs, losses and residuals are expressed as percentages of total water inputs or total water losses, respectively. Units are mm of runoff per water year (i.e., water-year discharge per unit catchment area).

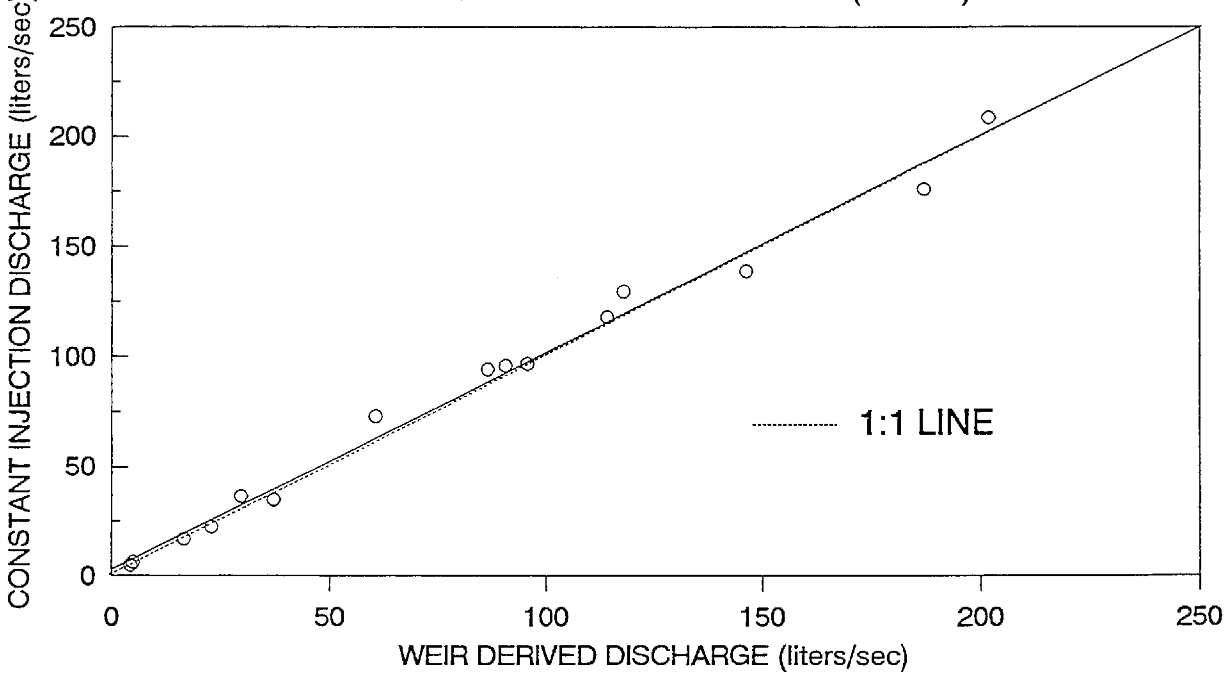
Figure II-50. Annual water balances for the Topaz Lake watershed from water years 1990 through 1993. In the bar graph, individual inputs, losses and residuals are expressed as percentages of total water inputs or total water losses, respectively. Units are mm of runoff per water year (i.e., water-year discharge per unit catchment area).

EMERALD OUTFLOW
WEIR DERIVED Q vs SLUG INJECTION Q (1991-94)



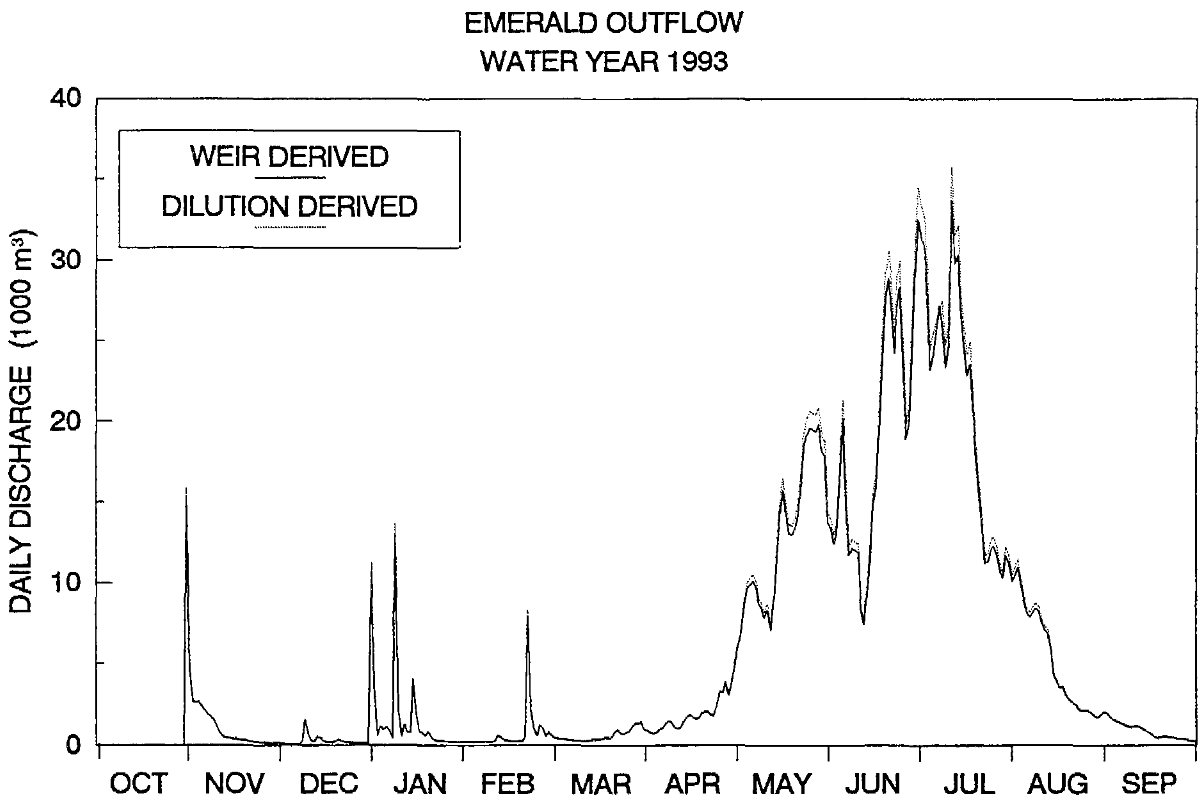
Y = 0.96 (X) + 12.8, R^2 = 0.94. STD ERROR = 20.1%

EMERALD OUTFLOW
WEIR DERIVED Q vs CONSTANT INJECTION Q (1993-94)



Y = 0.99 (X) + 3.02, R^2 = 0.99. STD ERROR = 6.5%

Figure II-1


EMERALD OUTFLOW
WATER YEAR 1993
WEIR DERIVED
DILUTION DERIVED
DAILY DISCHARGE (1000 m³)
0
10
20
30
40
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP

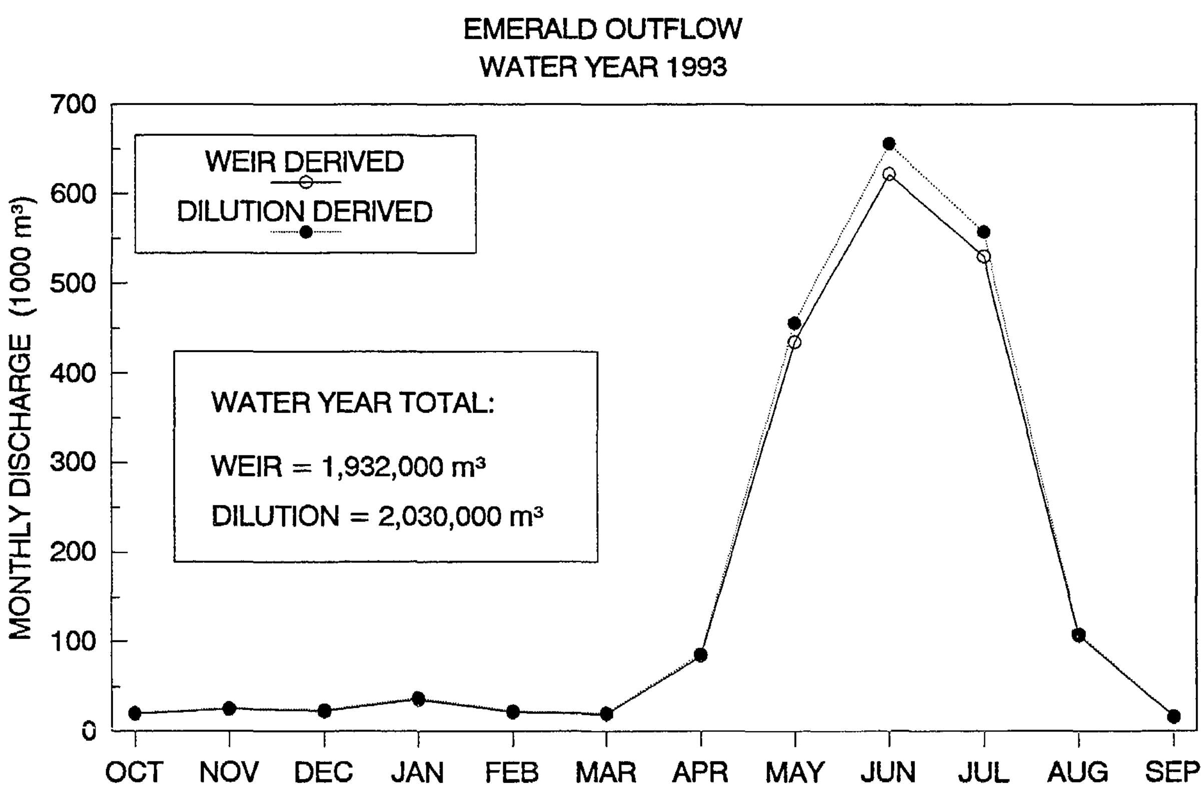
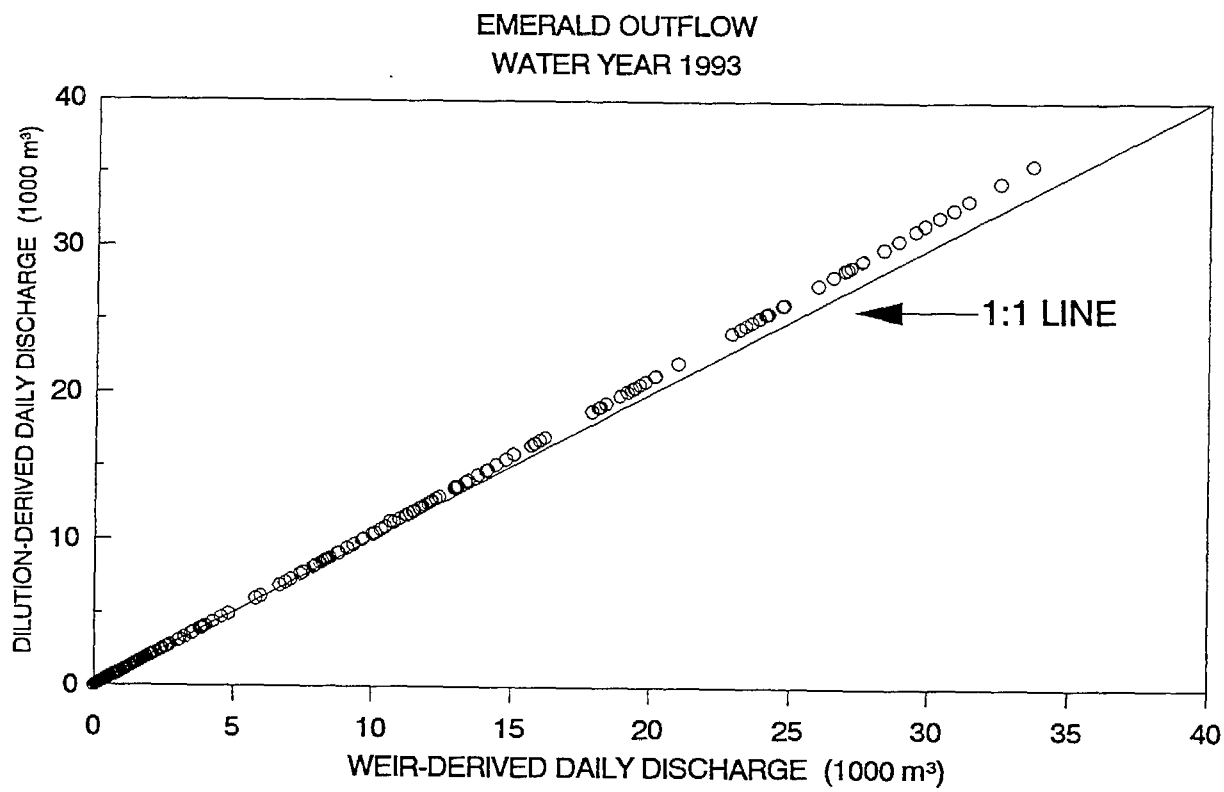

EMERALD OUTFLOW
WATER YEAR 1993
WEIR DERIVED
DILUTION DERIVED
WATER YEAR TOTAL:
WEIR = 1,932,000 m³
DILUTION = 2,030,000 m³
MONTHLY DISCHARGE (1000 m³)
0
100
200
300
400
500
600
700
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP

Figure II-2


EMERALD OUTFLOW
WATER YEAR 1993
DILUTION-DERIVED DAILY DISCHARGE (1000 m³)
WEIR-DERIVED DAILY DISCHARGE (1000 m³)
1:1 LINE
0
10
20
30
40
0
5
10
15
20
25
30
35
40

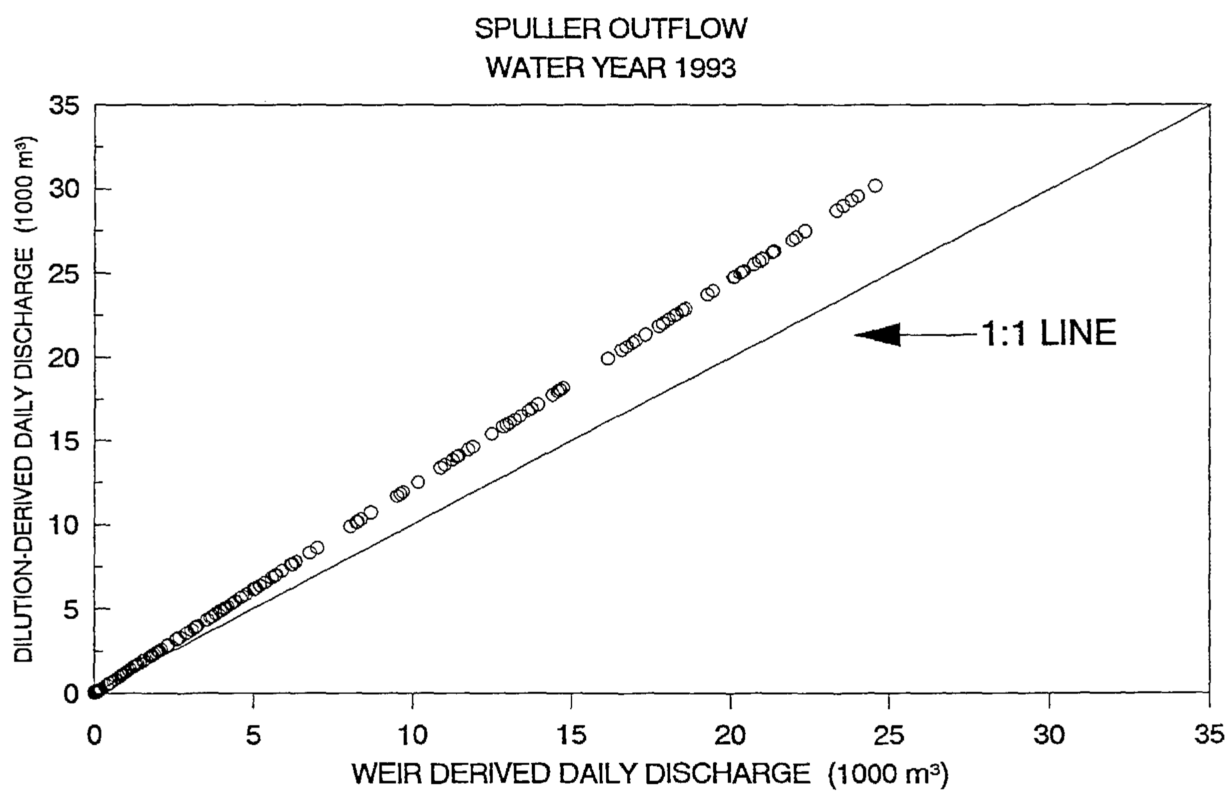
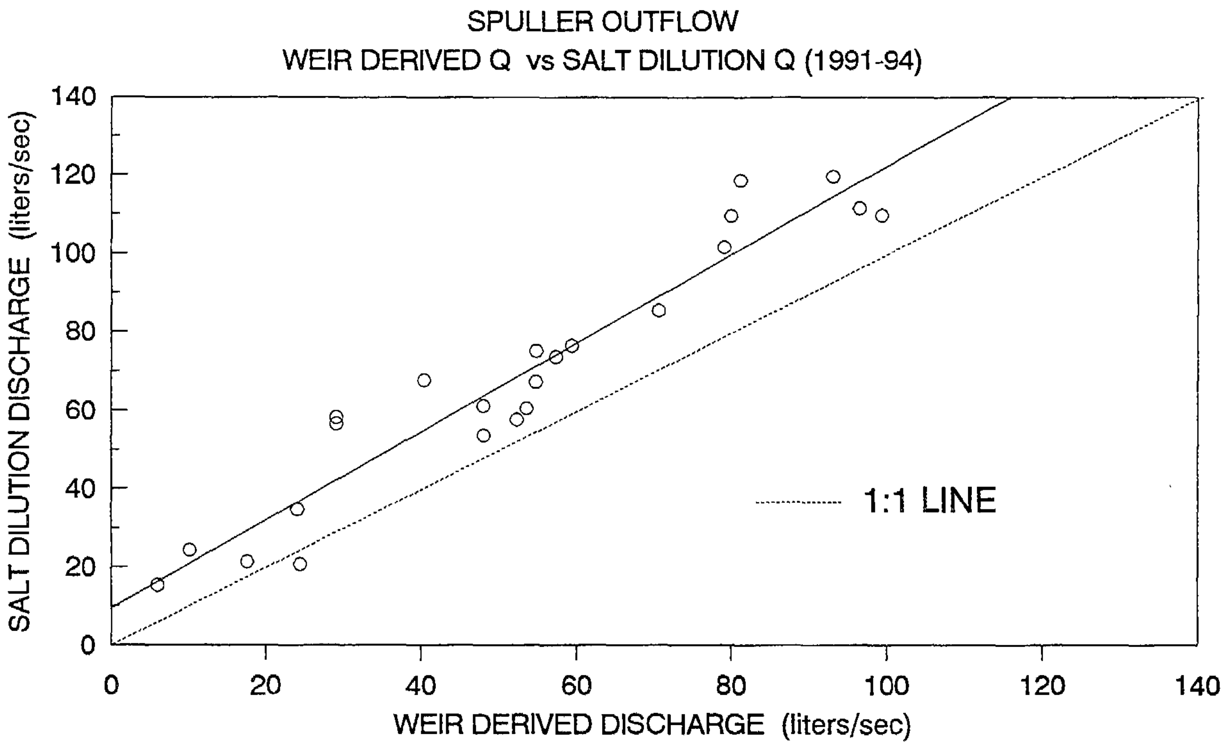
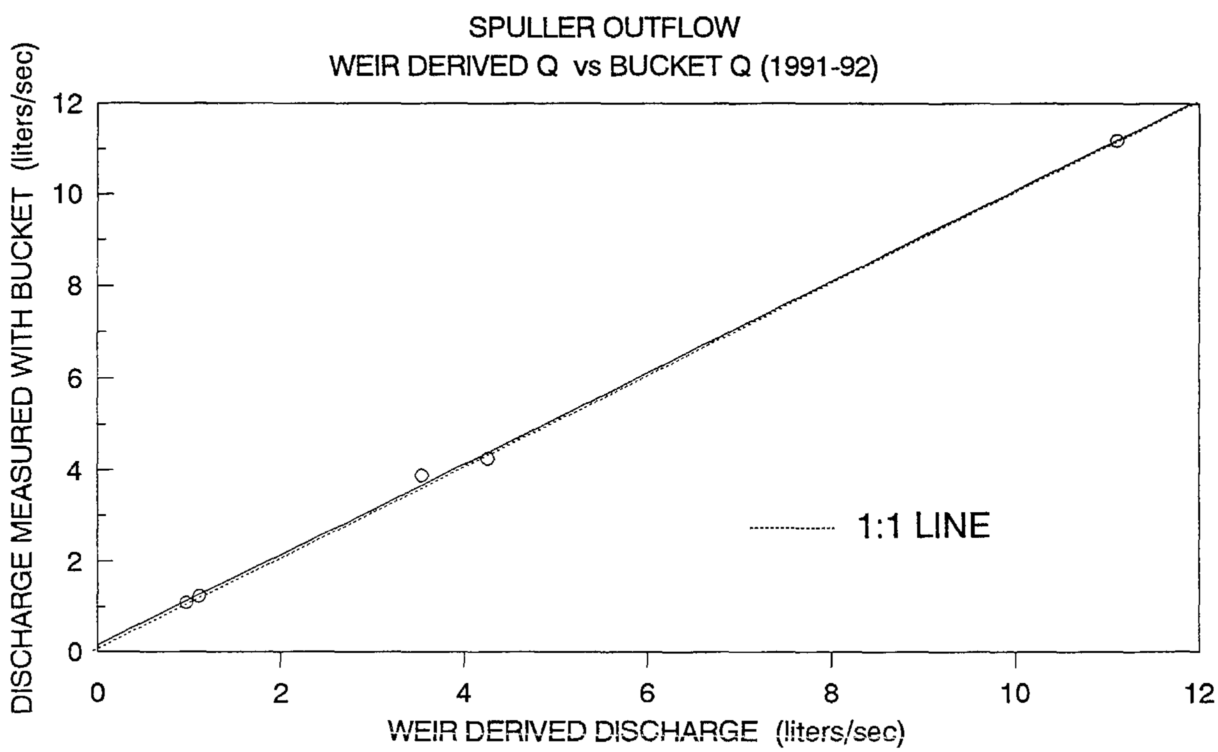

SPULLER OUTFLOW
WATER YEAR 1993
DILUTION-DERIVED DAILY DISCHARGE (1000 m³)
WEIR DERIVED DAILY DISCHARGE (1000 m³)
1:1 LINE
0
5
10
15
20
25
30
35
0
5
10
15
20
25
30
35

Figure II-3

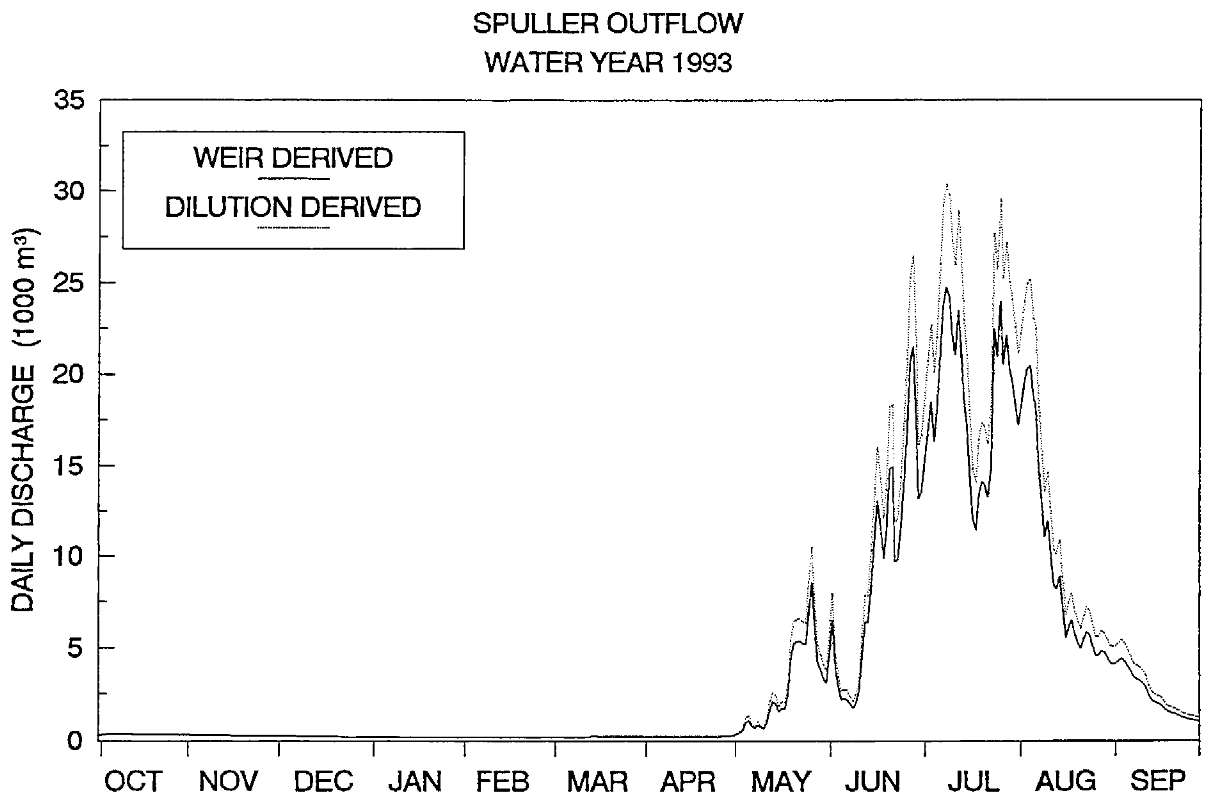


Y = 1.13(X) + 9.41; R^2=0.92. STD ERROR = 9.6%



Y = 0.99(X) + 0.15; R^2=1.00. STD ERROR = 0.1%

Figure II-4


SPULLER OUTFLOW
WATER YEAR 1993
WEIR DERIVED
DILUTION DERIVED
DAILY DISCHARGE (1000 m³)
35
30
25
20
15
10
5
0
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP

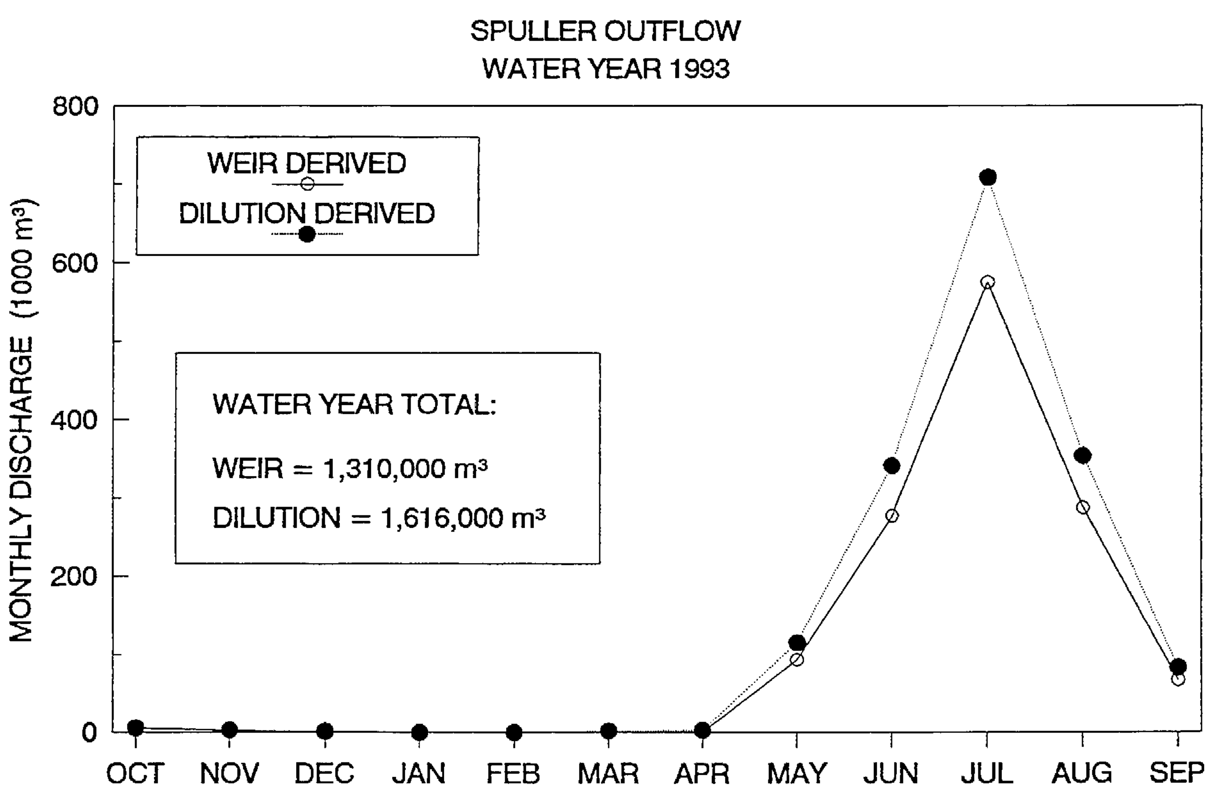

SPULLER OUTFLOW
WATER YEAR 1993
WEIR DERIVED
DILUTION DERIVED
WATER YEAR TOTAL:
WEIR = 1,310,000 m³
DILUTION = 1,616,000 m³
MONTHLY DISCHARGE (1000 m³)
800
600
400
200
0
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP

Figure II-5

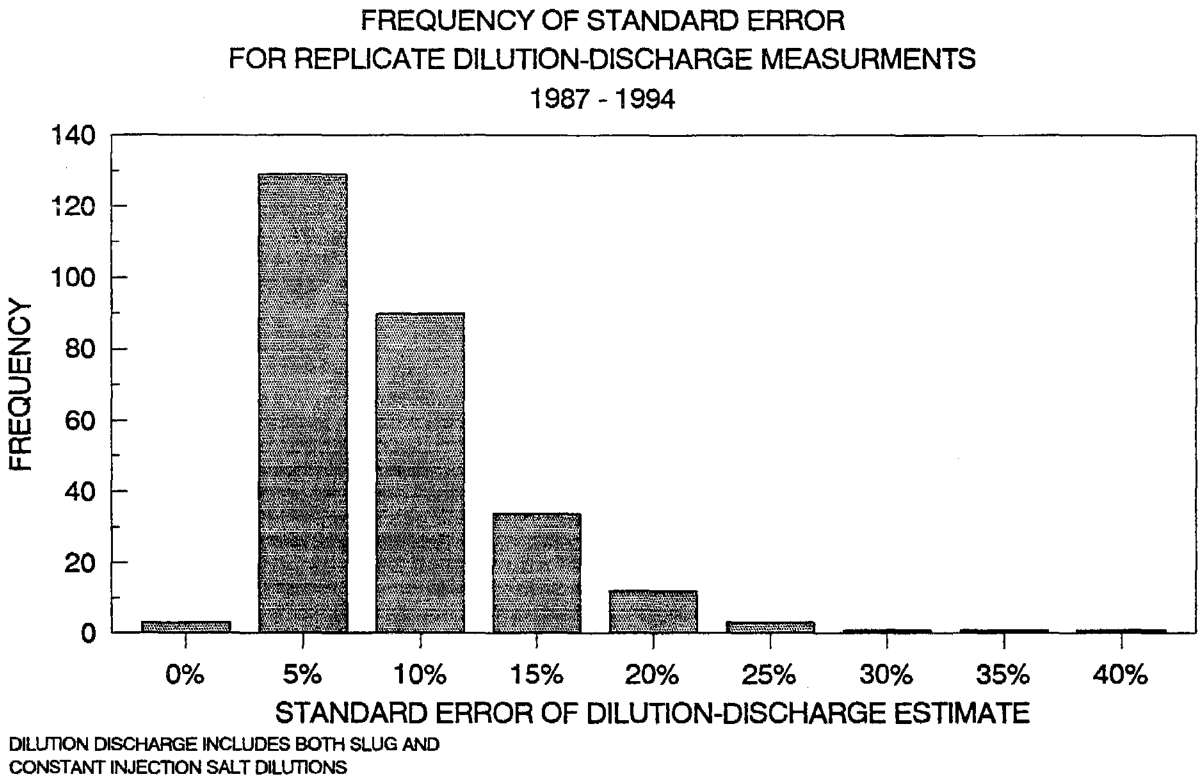
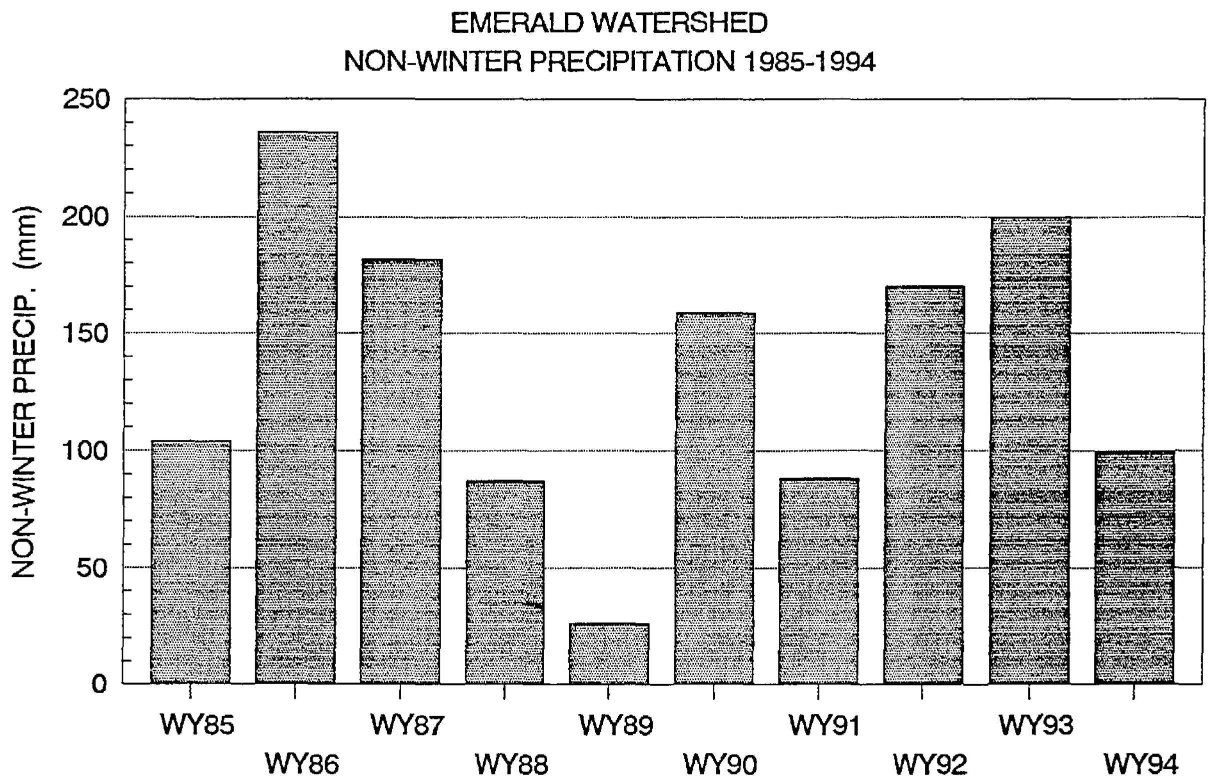

FREQUENCY OF STANDARD ERROR
FOR REPLICATE DILUTION-DISCHARGE MEASURMENTS
1987 - 1994
FREQUENCY
140
120
100
80
60
40
20
0
0%
5%
10%
15%
20%
25%
30%
35%
40%
STANDARD ERROR OF DILUTION-DISCHARGE ESTIMATE
DILUTION DISCHARGE INCLUDES BOTH SLUG AND
CONSTANT INJECTION SALT DILUTIONS

Figure II-6


EMERALD WATERSHED
NON-WINTER PRECIPITATION 1985-1994
NON-WINTER PRECIP. (mm)
250
200
150
100
50
0
WY85
WY86
WY87
WY88
WY89
WY90
WY91
WY92
WY93
WY94

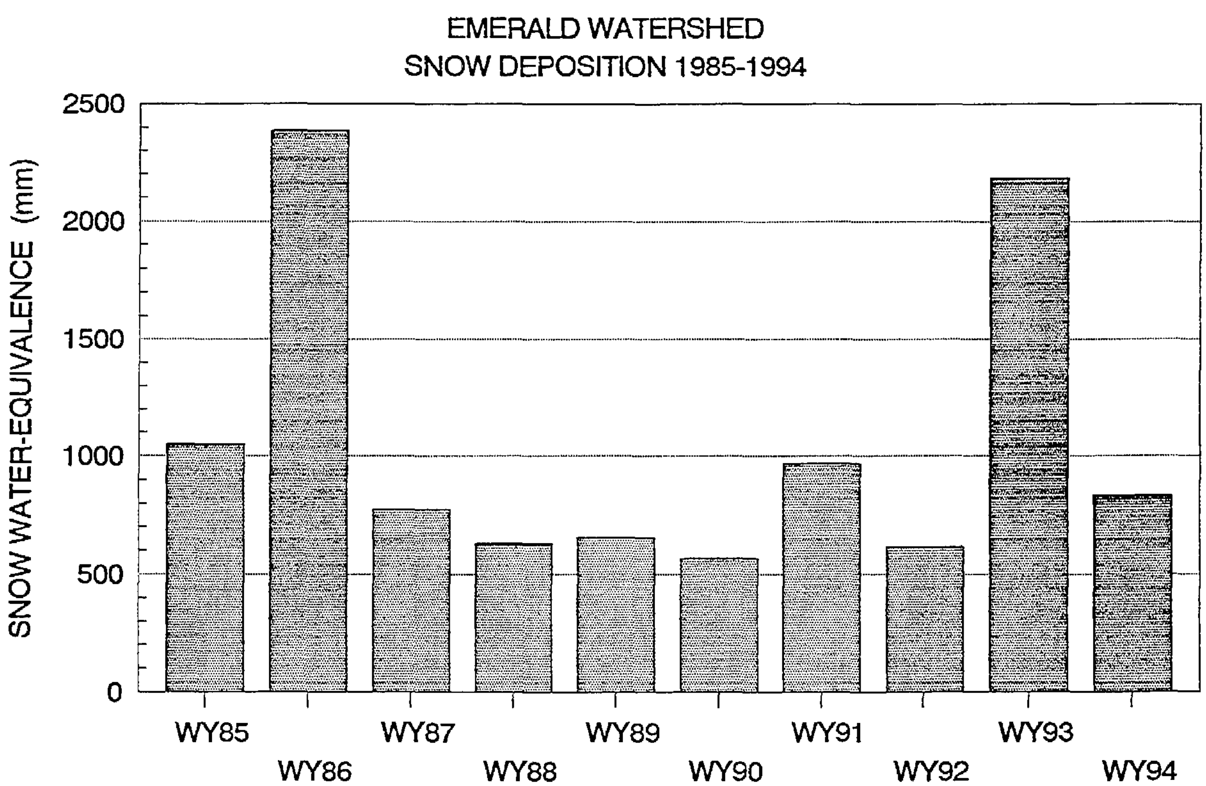
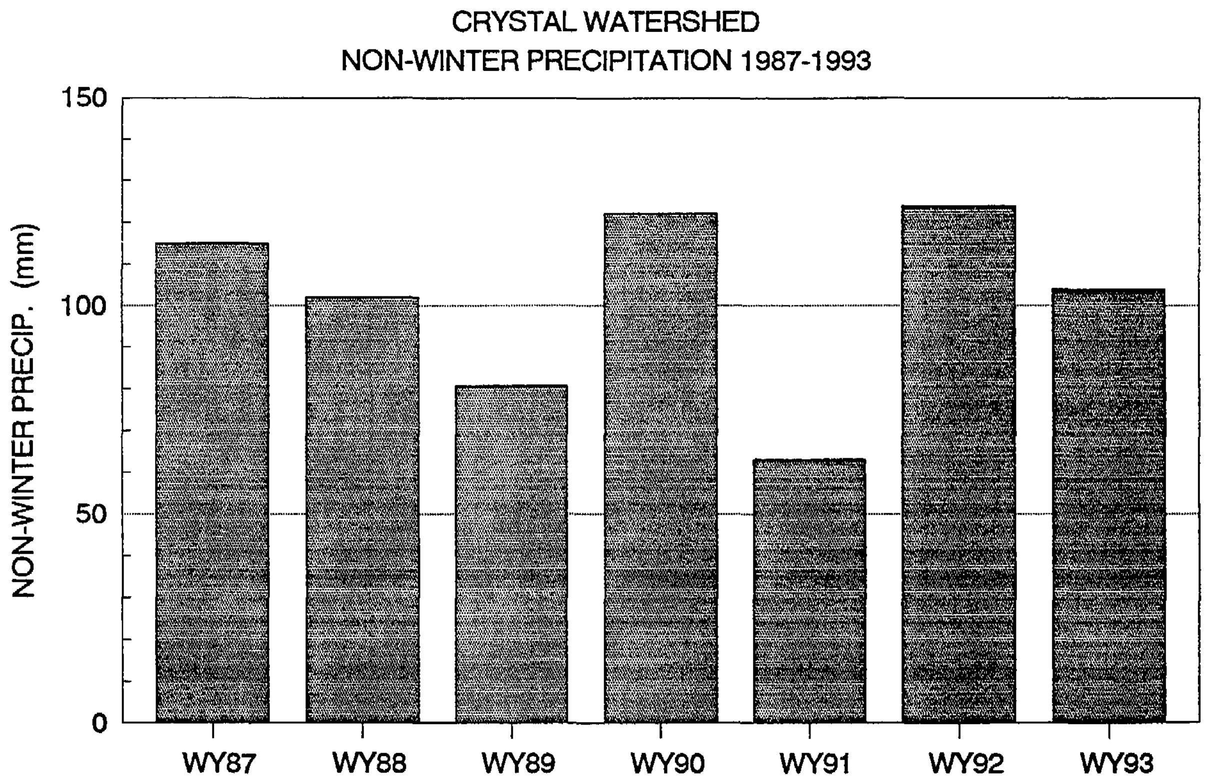

EMERALD WATERSHED
SNOW DEPOSITION 1985-1994
SNOW WATER-EQUIVALENCE (mm)
2500
2000
1500
1000
500
0
WY85
WY86
WY87
WY88
WY89
WY90
WY91
WY92
WY93
WY94

Figure II-7


CRYSTAL WATERSHED
NON-WINTER PRECIPITATION 1987-1993
NON-WINTER PRECIP. (mm)
150
100
50
0
WY87
WY88
WY89
WY90
WY91
WY92
WY93

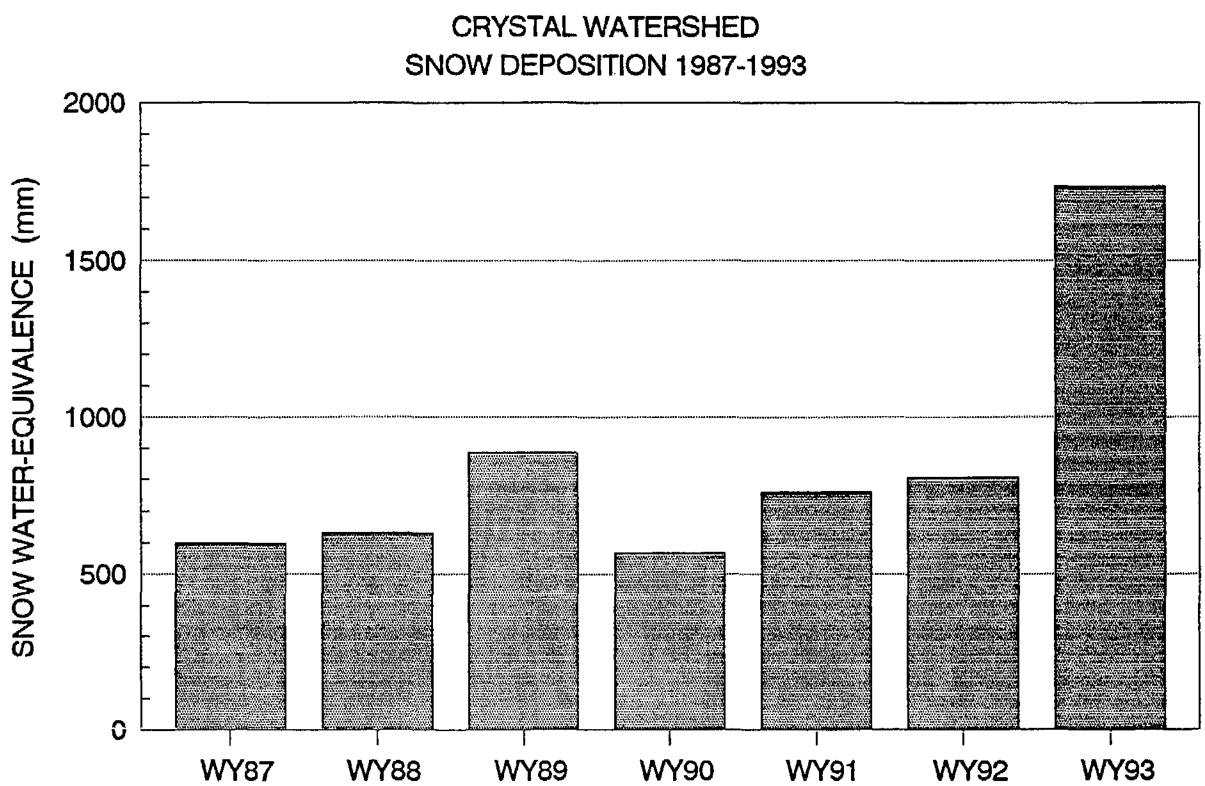
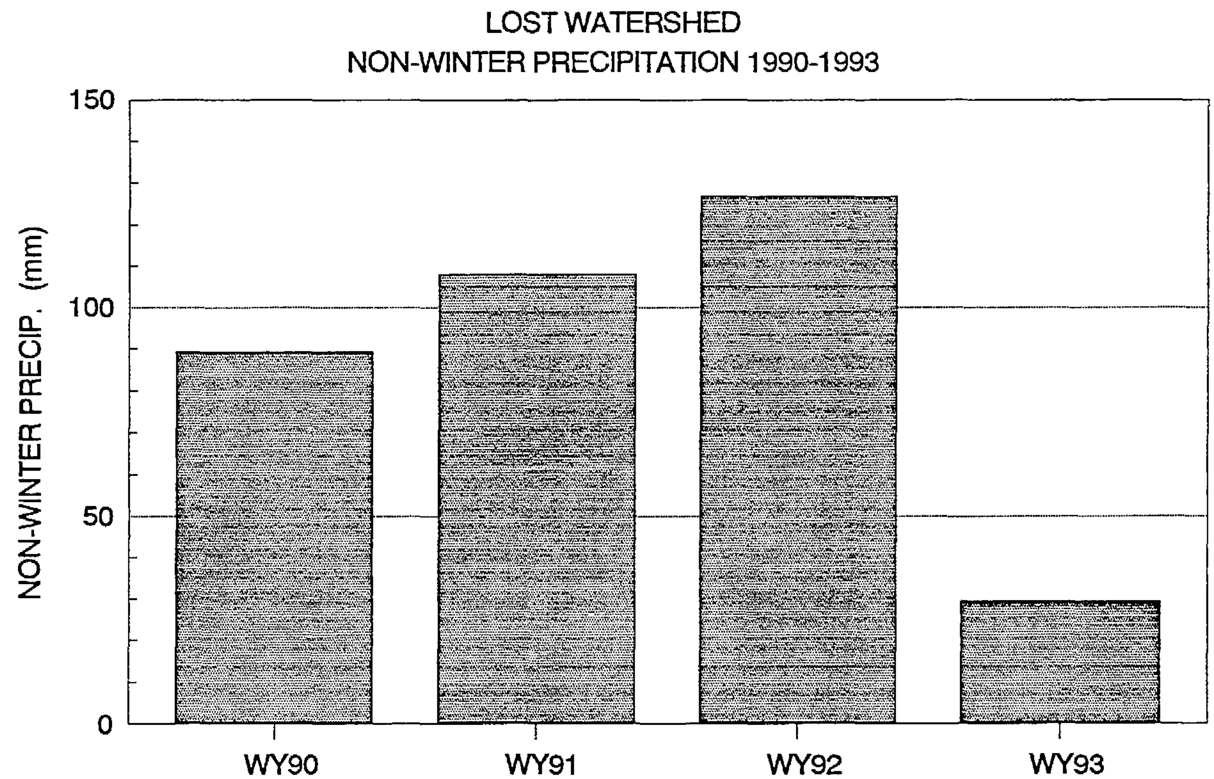

CRYSTAL WATERSHED
SNOW DEPOSITION 1987-1993
SNOW WATER-EQUIVALENCE (mm)
2000
1500
1000
500
0
WY87
WY88
WY89
WY90
WY91
WY92
WY93

Figure II-8


LOST WATERSHED
NON-WINTER PRECIPITATION 1990-1993
NON-WINTER PRECIP. (mm)
150
100
50
0
WY90
WY91
WY92
WY93

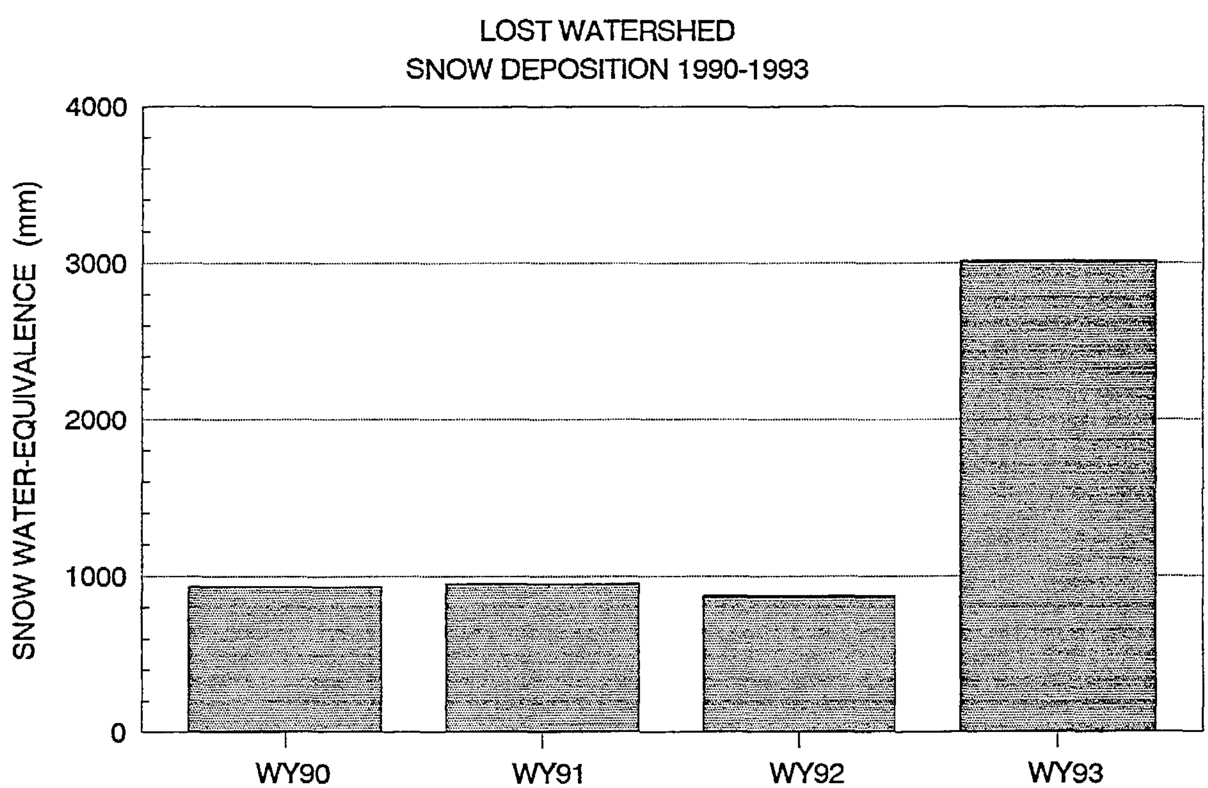

LOST WATERSHED
SNOW DEPOSITION 1990-1993
SNOW WATER-EQUIVALENCE (mm)
4000
3000
2000
1000
0
WY90
WY91
WY92
WY93

Figure II-9

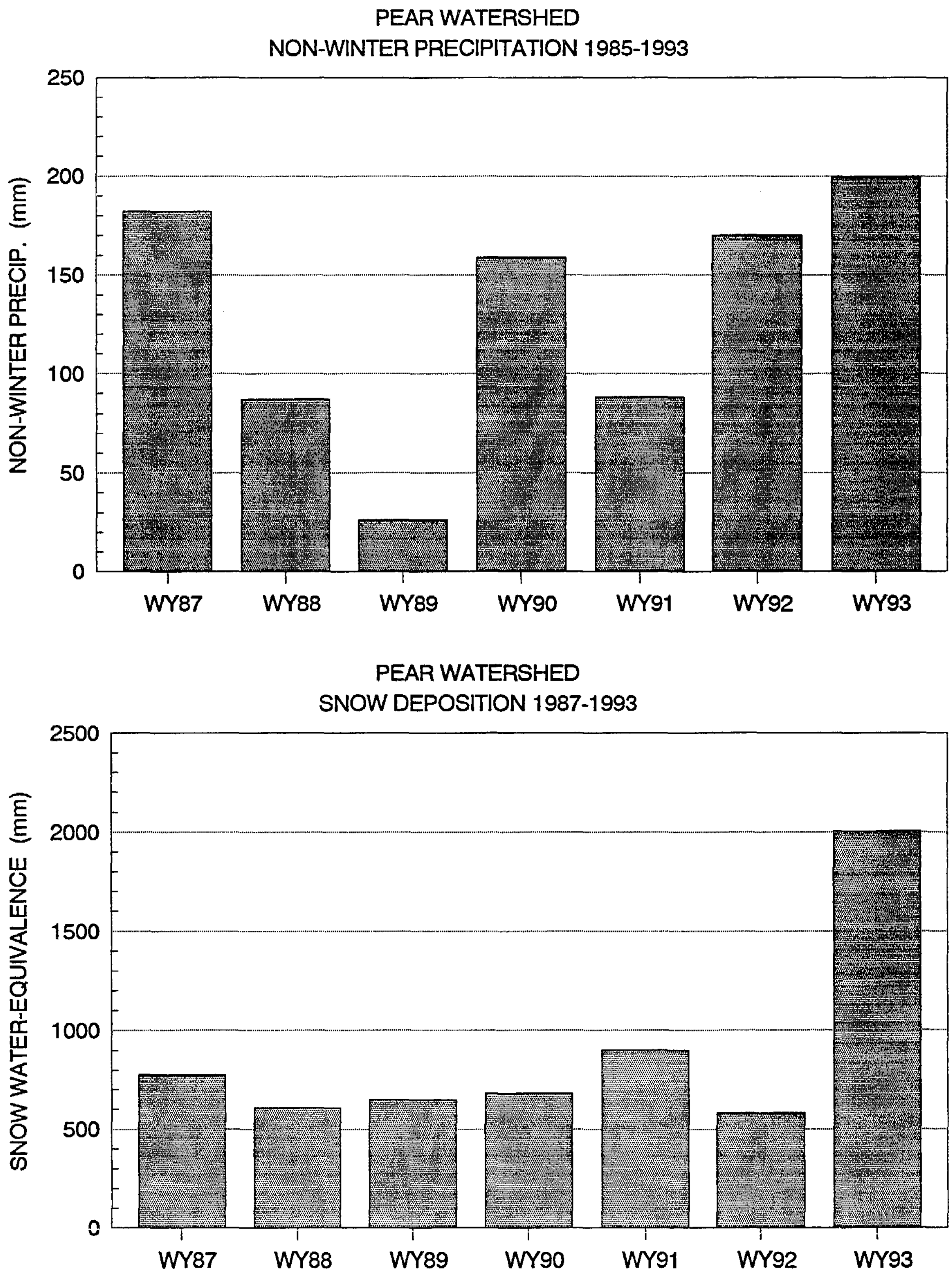
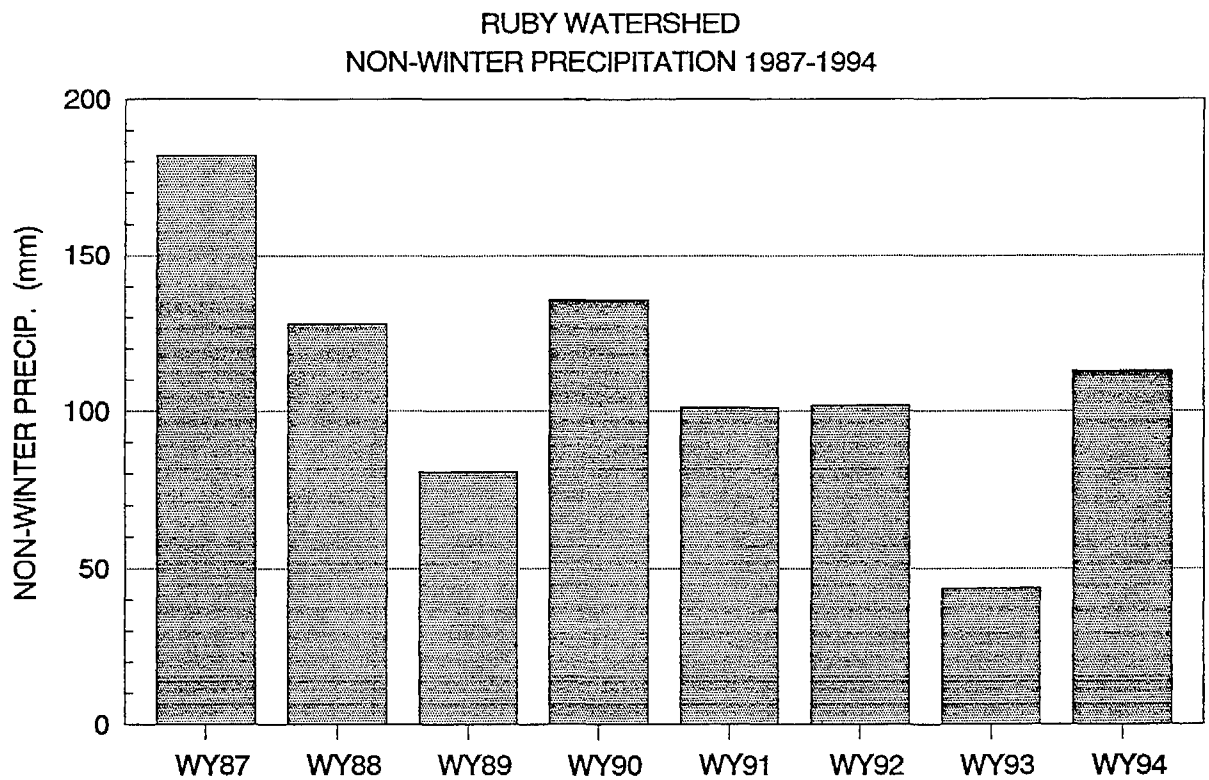

PEAR WATERSHED
NON-WINTER PRECIPITATION 1985-1993
NON-WINTER PRECIP. (mm)
250
200
150
100
50
0
WY87
WY88
WY89
WY90
WY91
WY92
WY93
PEAR WATERSHED
SNOW DEPOSITION 1987-1993
SNOW WATER-EQUIVALENCE (mm)
2500
2000
1500
1000
500
0
WY87
WY88
WY89
WY90
WY91
WY92
WY93

Figure II-10


RUBY WATERSHED
NON-WINTER PRECIPITATION 1987-1994
NON-WINTER PRECIP. (mm)
200
150
100
50
0
WY87
WY88
WY89
WY90
WY91
WY92
WY93
WY94

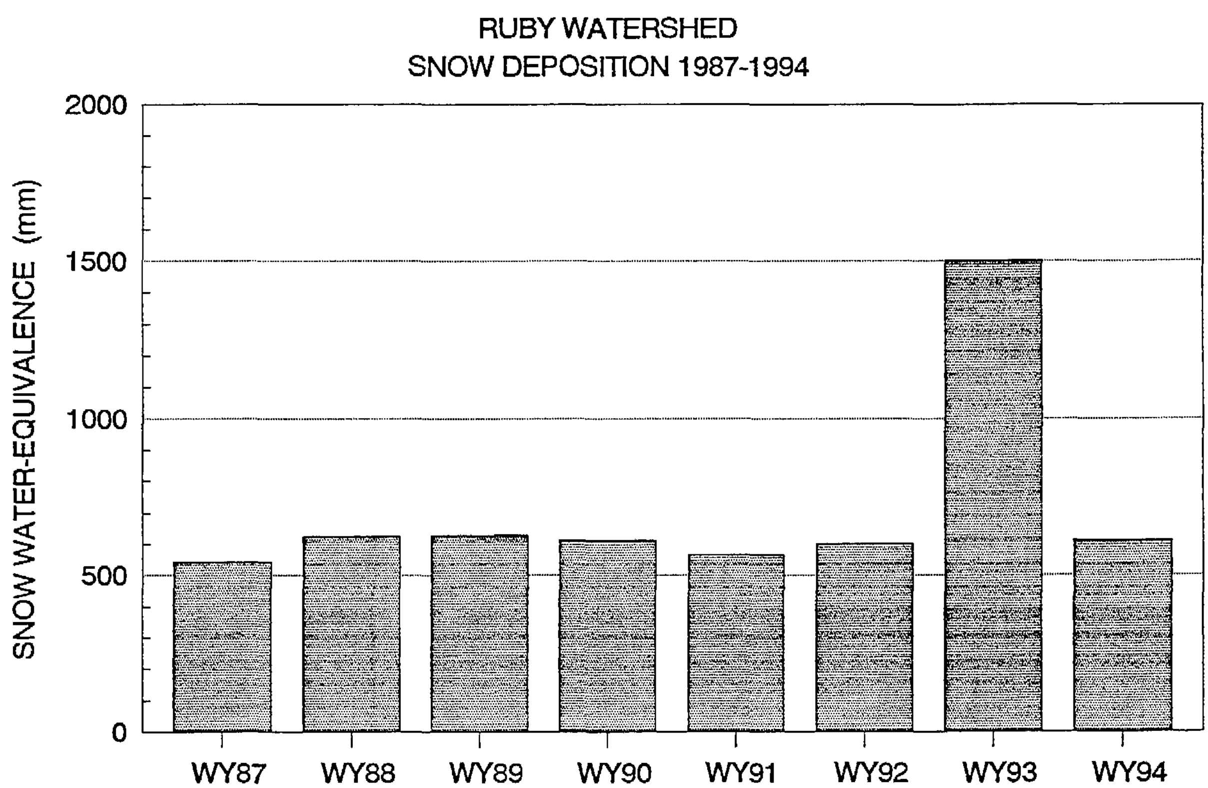

RUBY WATERSHED
SNOW DEPOSITION 1987-1994
SNOW WATER-EQUIVALENCE (mm)
2000
1500
1000
500
0
WY87
WY88
WY89
WY90
WY91
WY92
WY93
WY94

Figure II-11

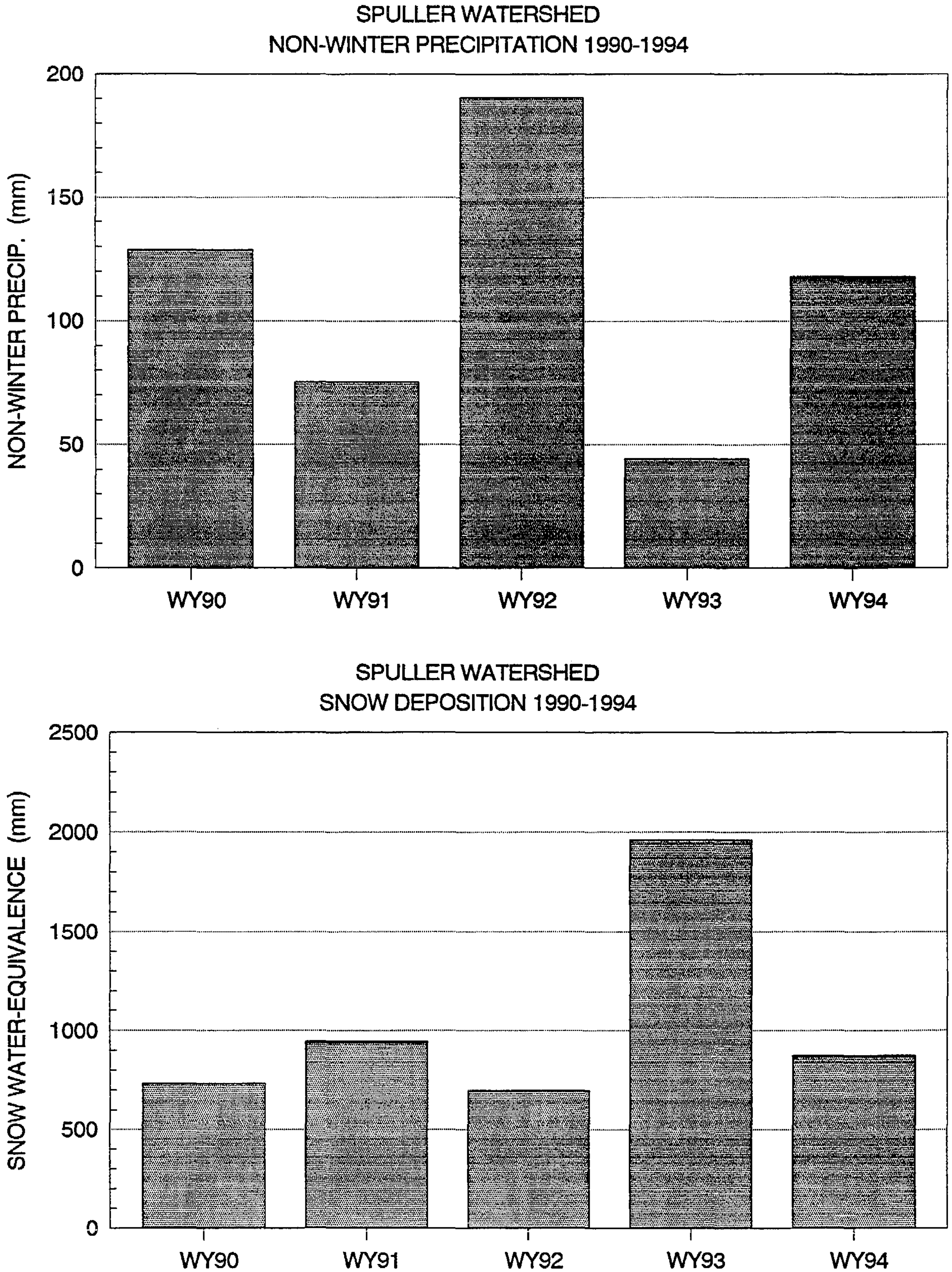

SPULLER WATERSHED
NON-WINTER PRECIPITATION 1990-1994
NON-WINTER PRECIP. (mm)
200
150
100
50
0
WY90
WY91
WY92
WY93
WY94
SPULLER WATERSHED
SNOW DEPOSITION 1990-1994
SNOW WATER-EQUIVALENCE (mm)
2500
2000
1500
1000
500
0
WY90
WY91
WY92
WY93
WY94

Figure II-12

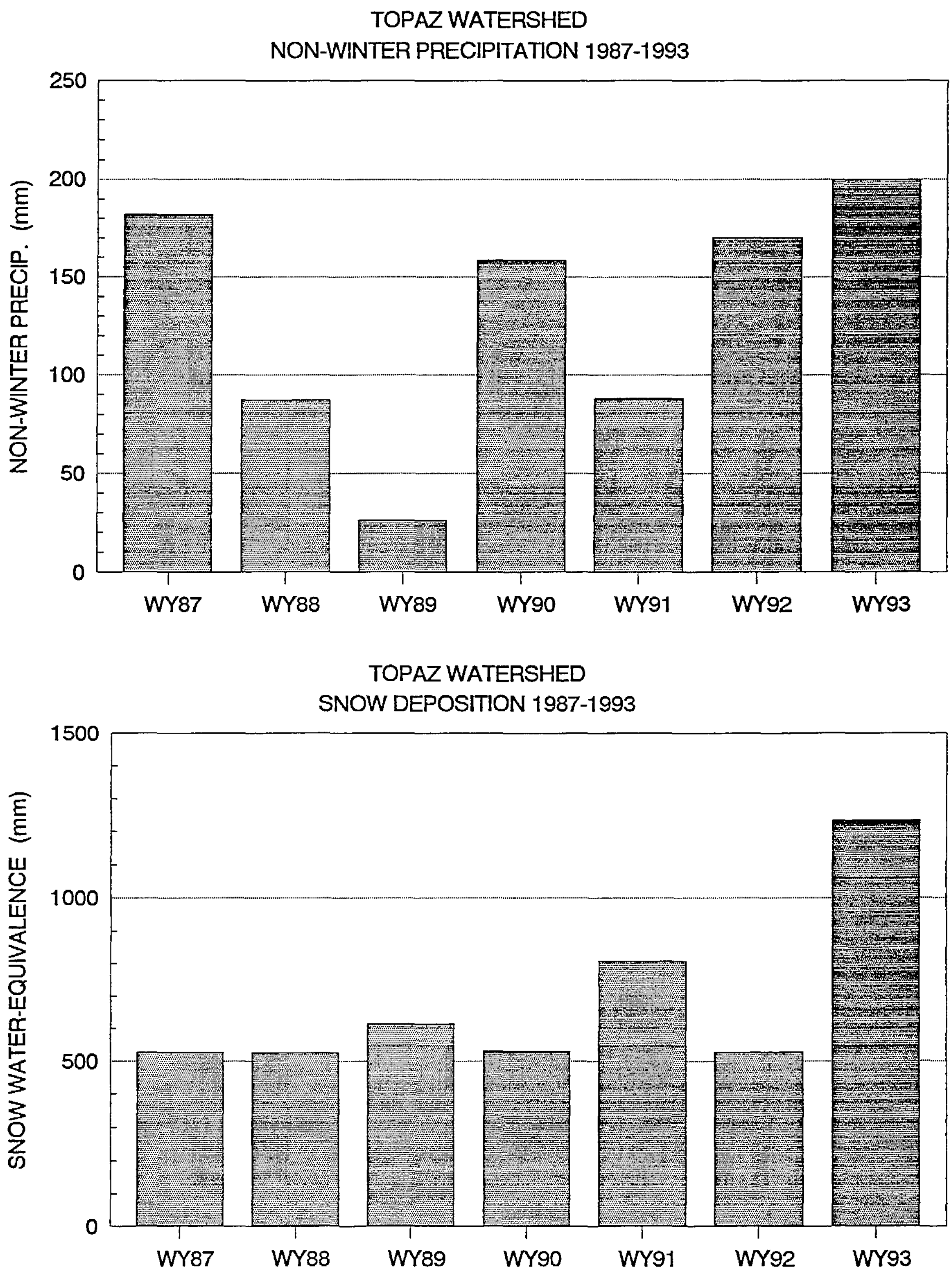
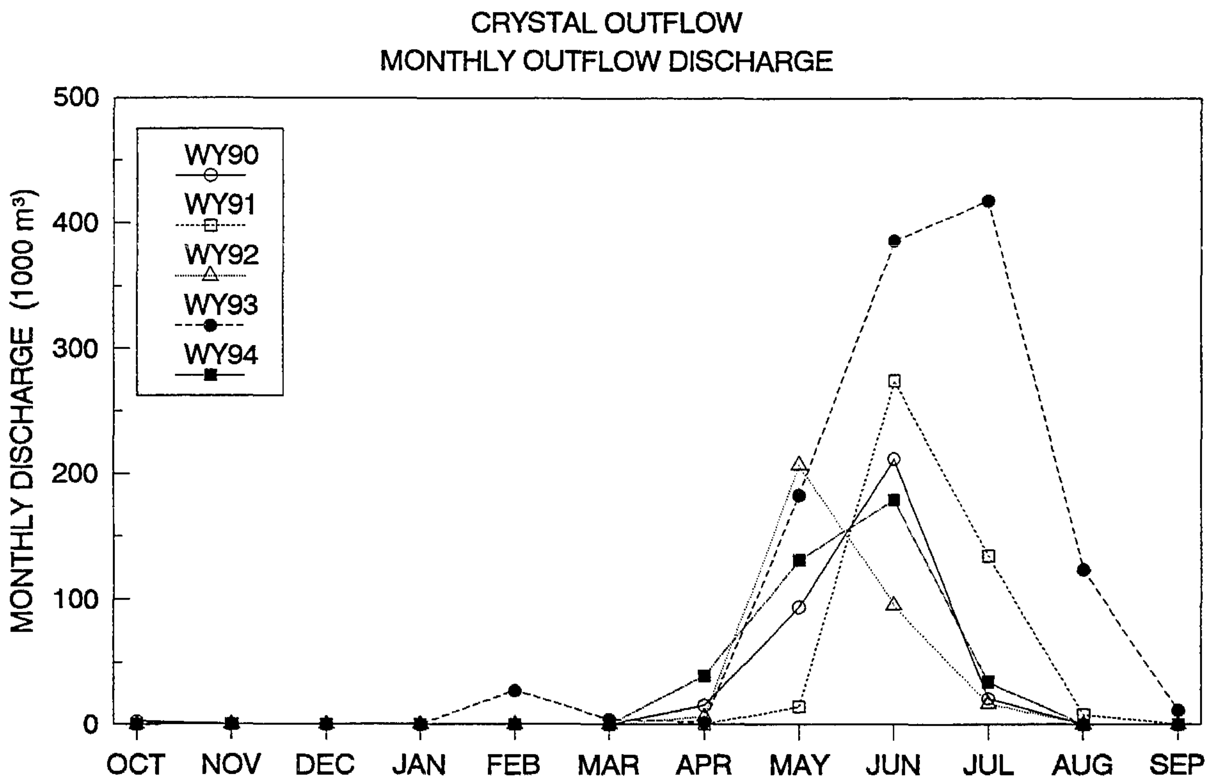
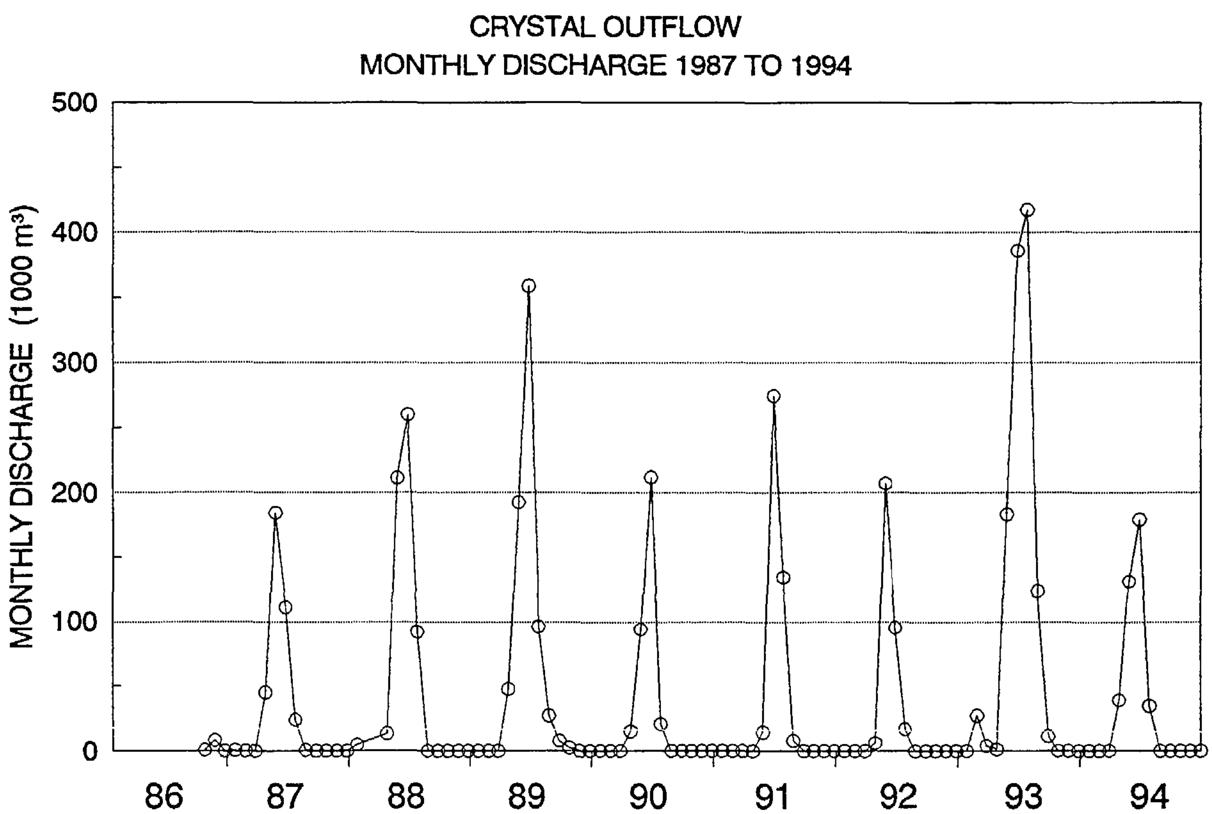

TOPAZ WATERSHED
NON-WINTER PRECIPITATION 1987-1993
NON-WINTER PRECIP. (mm)
250
200
150
100
50
0
WY87
WY88
WY89
WY90
WY91
WY92
WY93
TOPAZ WATERSHED
SNOW DEPOSITION 1987-1993
SNOW WATER-EQUIVALENCE (mm)
1500
1000
500
0
WY87
WY88
WY89
WY90
WY91
WY92
WY93

Figure II-13

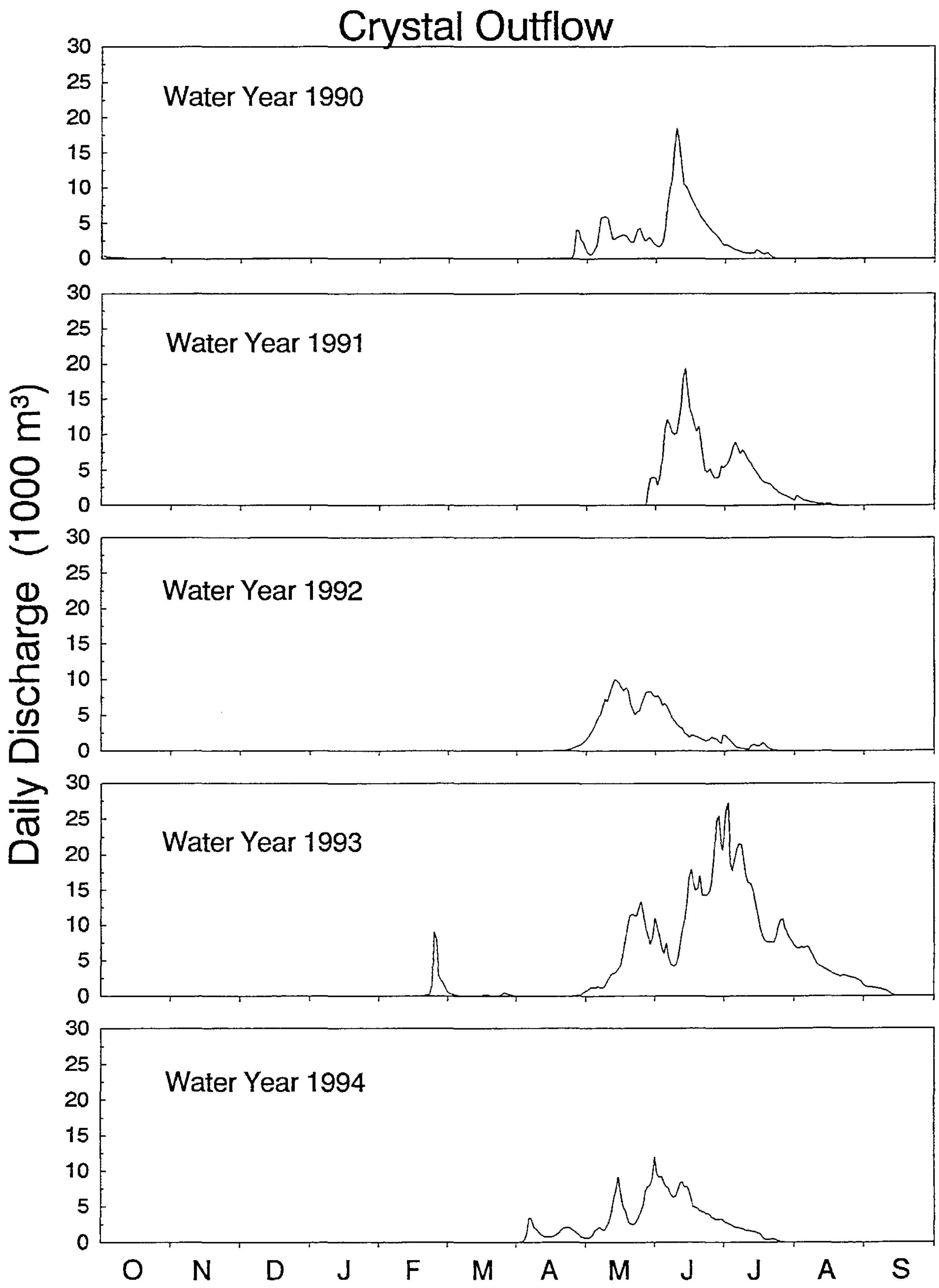


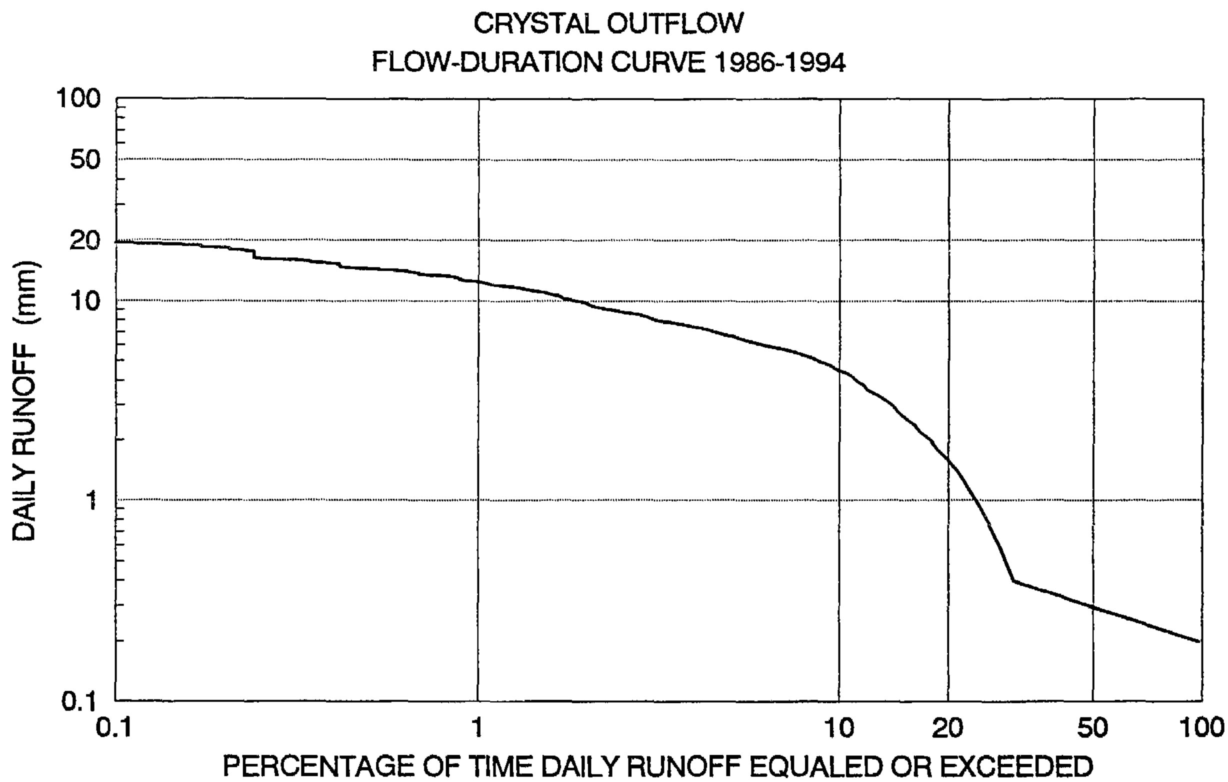
CRYSTAL OUTFLOW
MONTHLY OUTFLOW DISCHARGE
MONTHLY DISCHARGE (1000 m³)
WY90
WY91
WY92
WY93
WY94
0
100
200
300
400
500
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP



CRYSTAL OUTFLOW
MONTHLY DISCHARGE 1987 TO 1994
MONTHLY DISCHARGE (1000 m³)
0
100
200
300
400
500
86
87
88
89
90
91
92
93
94

Figure II-14


Crystal Outflow
Water Year 1990
Water Year 1991
Water Year 1992
Water Year 1993
Water Year 1994
Daily Discharge (1000 m³)
30
25
20
15
10
5
0
O N D J F M A M J J A S
Figure II-15


CRYSTAL OUTFLOW
FLOW-DURATION CURVE 1986-1994
DAILY RUNOFF (mm)
100
50
20
10
1
0.1
0.1
1
10
20
50
100
PERCENTAGE OF TIME DAILY RUNOFF EQUALED OR EXCEEDED

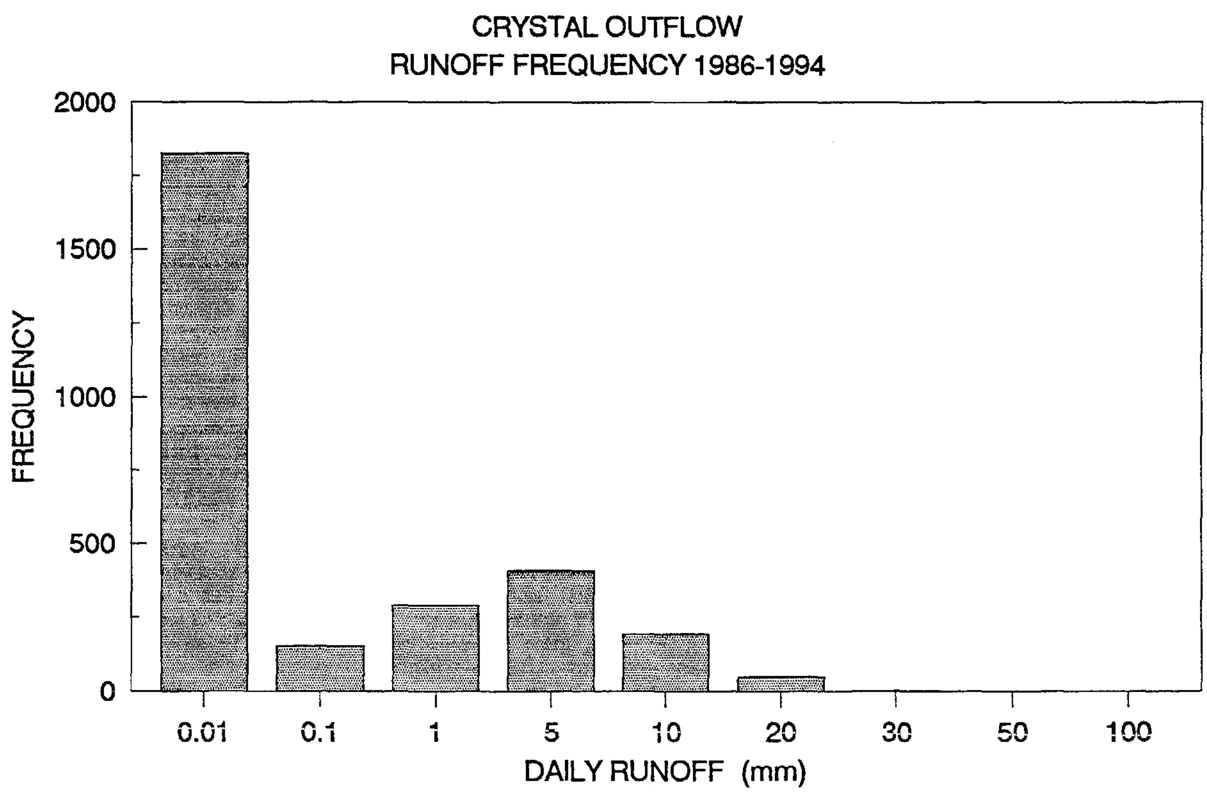
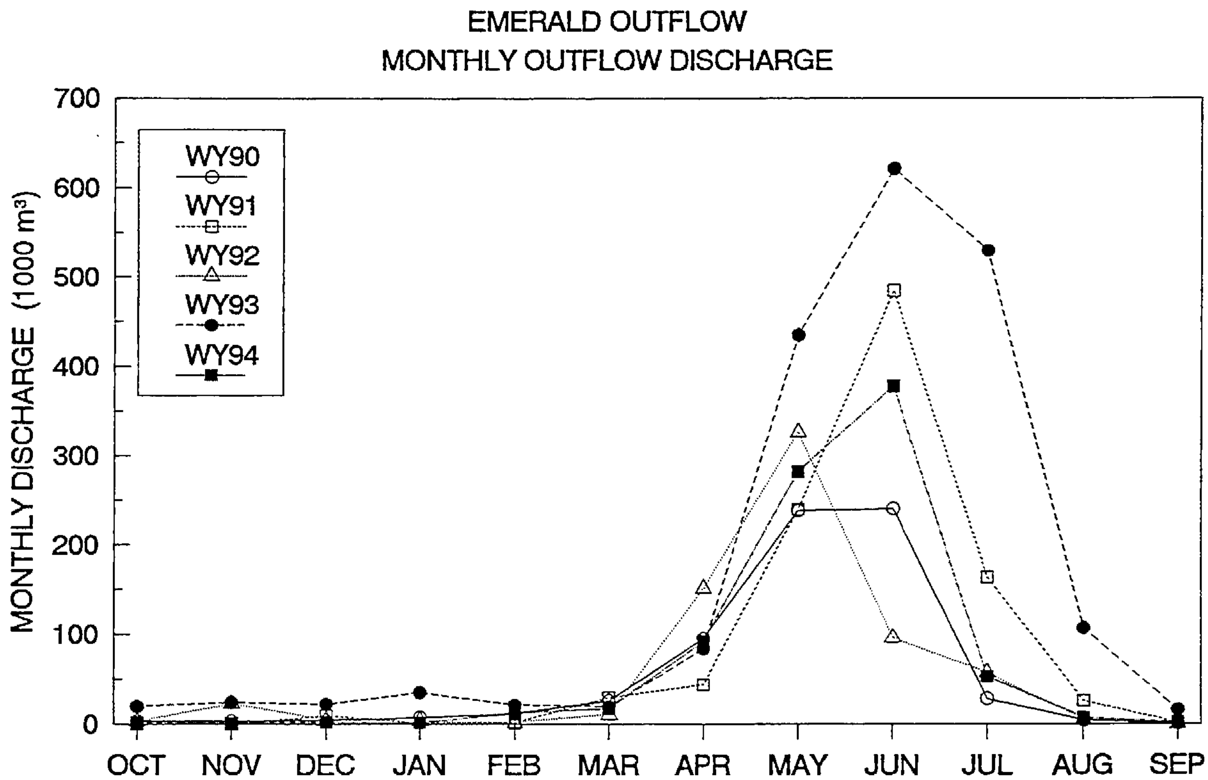

CRYSTAL OUTFLOW
RUNOFF FREQUENCY 1986-1994
FREQUENCY
2000
1500
1000
500
0
0.01
0.1
1
5
10
20
30
50
100
DAILY RUNOFF (mm)

Figure II-16


EMERALD OUTFLOW
MONTHLY OUTFLOW DISCHARGE
MONTHLY DISCHARGE (1000 m³)
WY90
WY91
WY92
WY93
WY94
0
100
200
300
400
500
600
700
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP

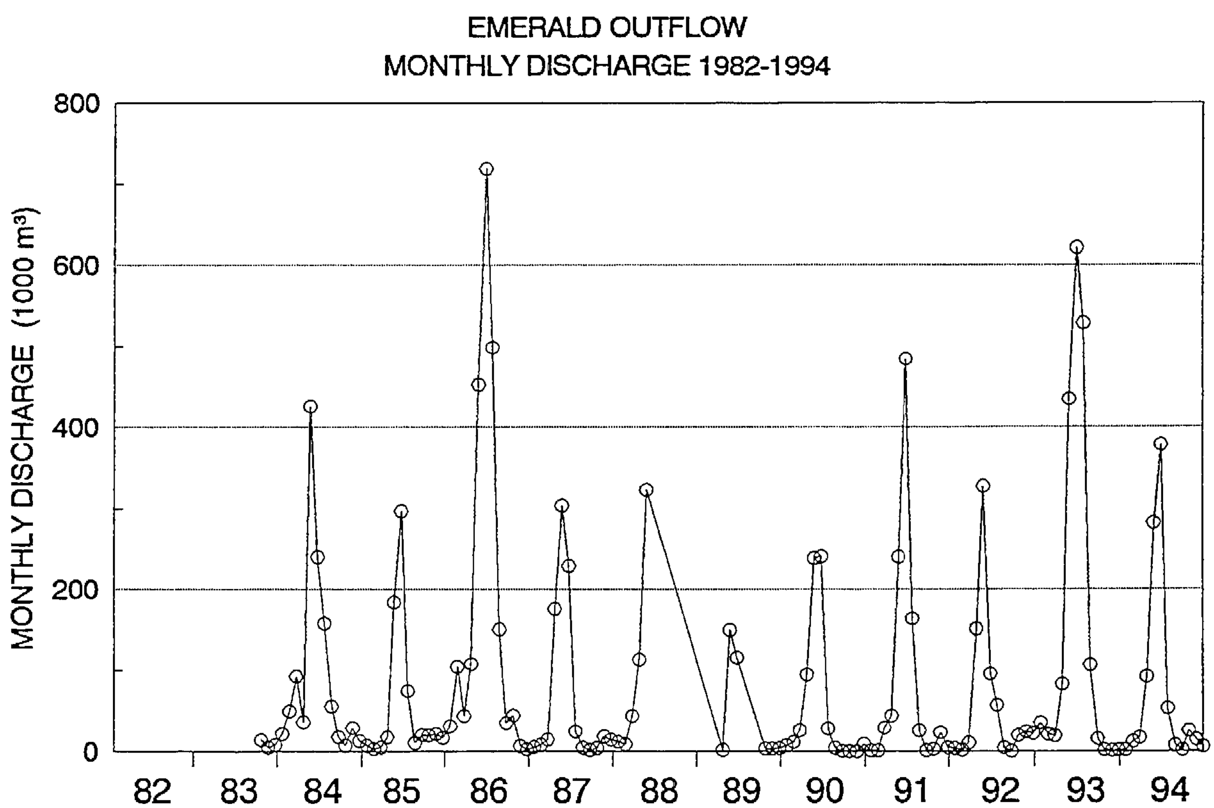
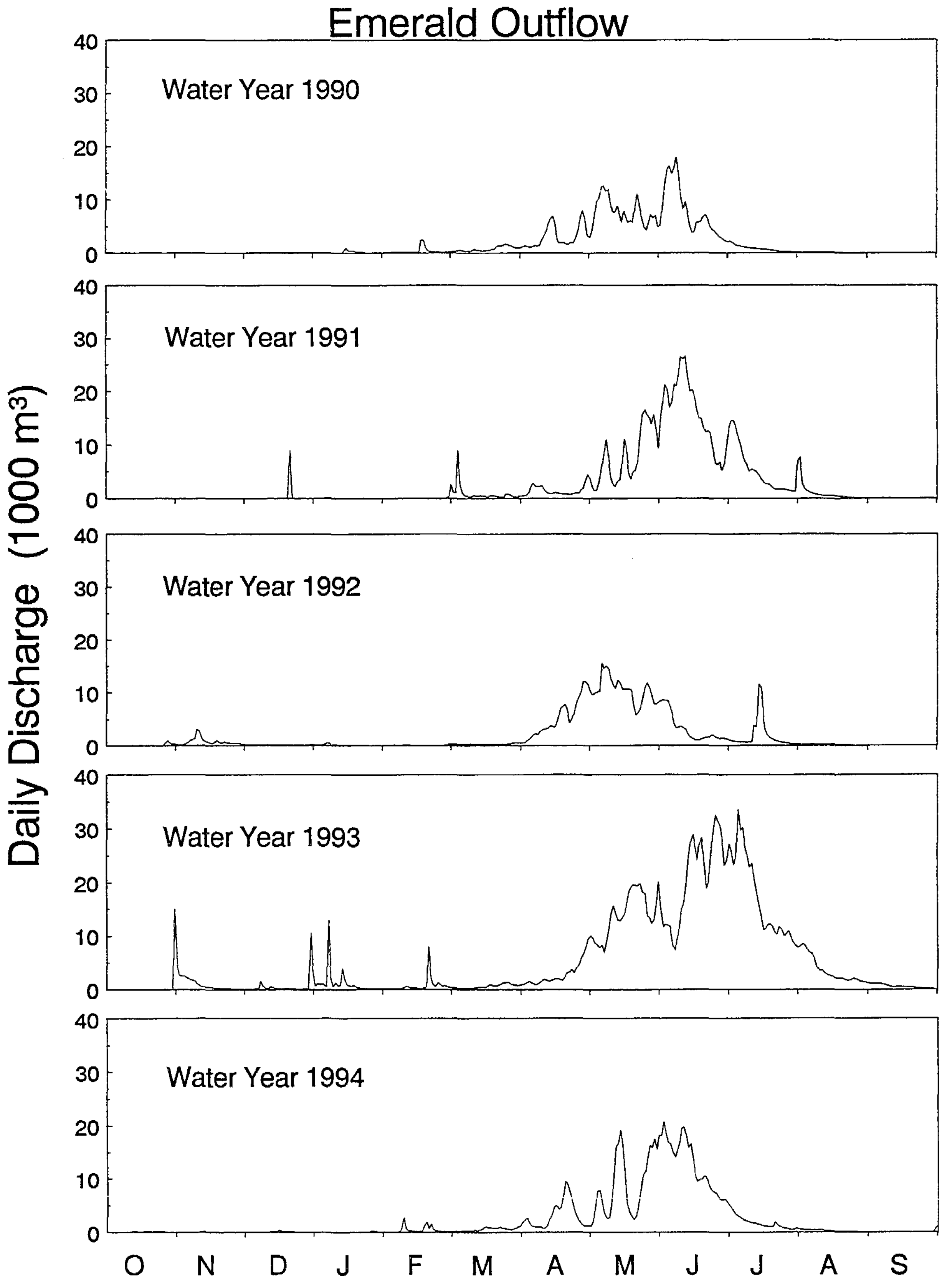

EMERALD OUTFLOW
MONTHLY DISCHARGE 1982-1994
MONTHLY DISCHARGE (1000 m³)
0
200
400
600
800
82 83 84 85 86 87 88 89 90 91 92 93 94

Figure II-17



Emerald Outflow
Water Year 1990
Water Year 1991
Water Year 1992
Water Year 1993
Water Year 1994
Daily Discharge (1000 m³)
0
10
20
30
40
O
N
D
J
F
M
A
M
J
J
A
S

Figure II-18

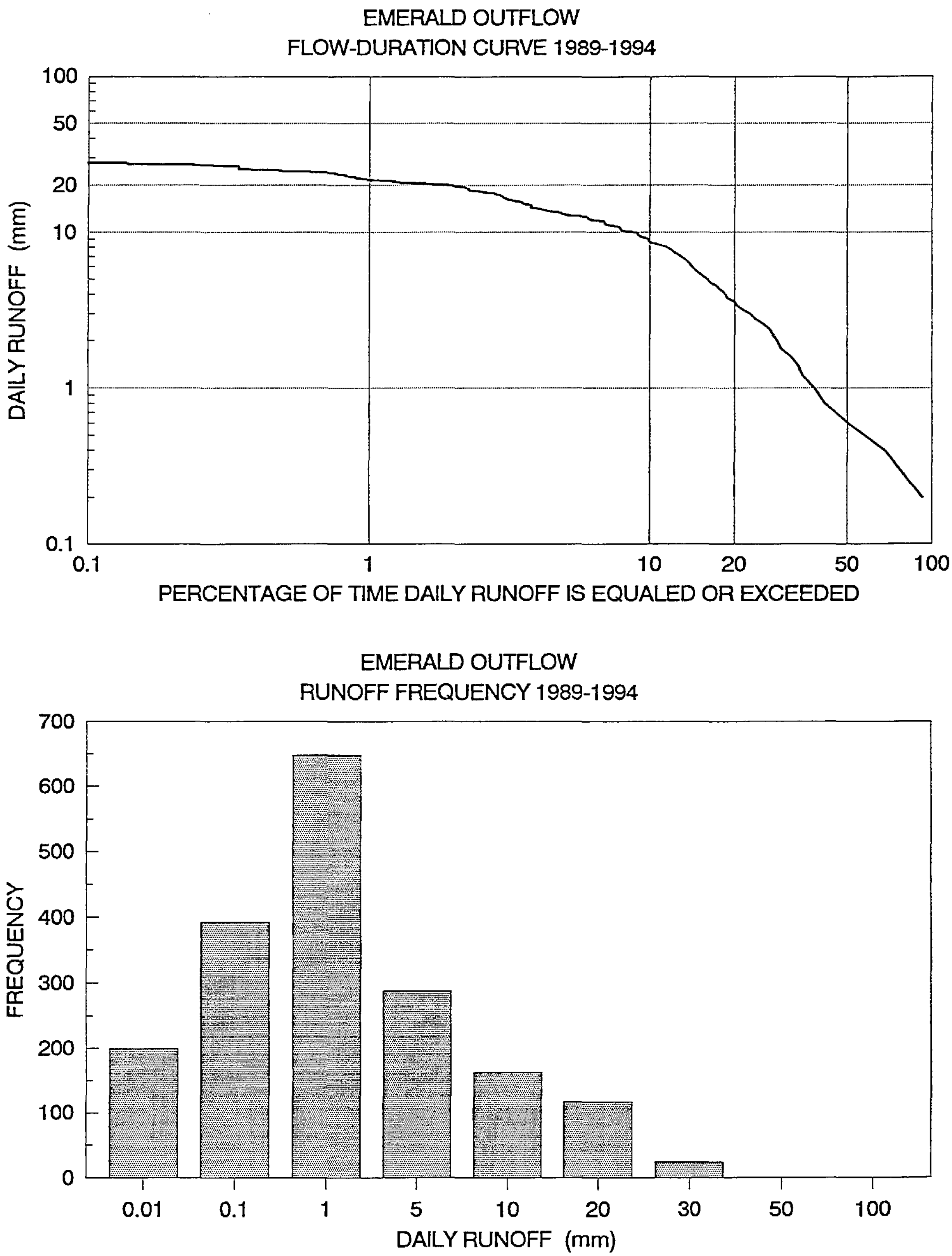
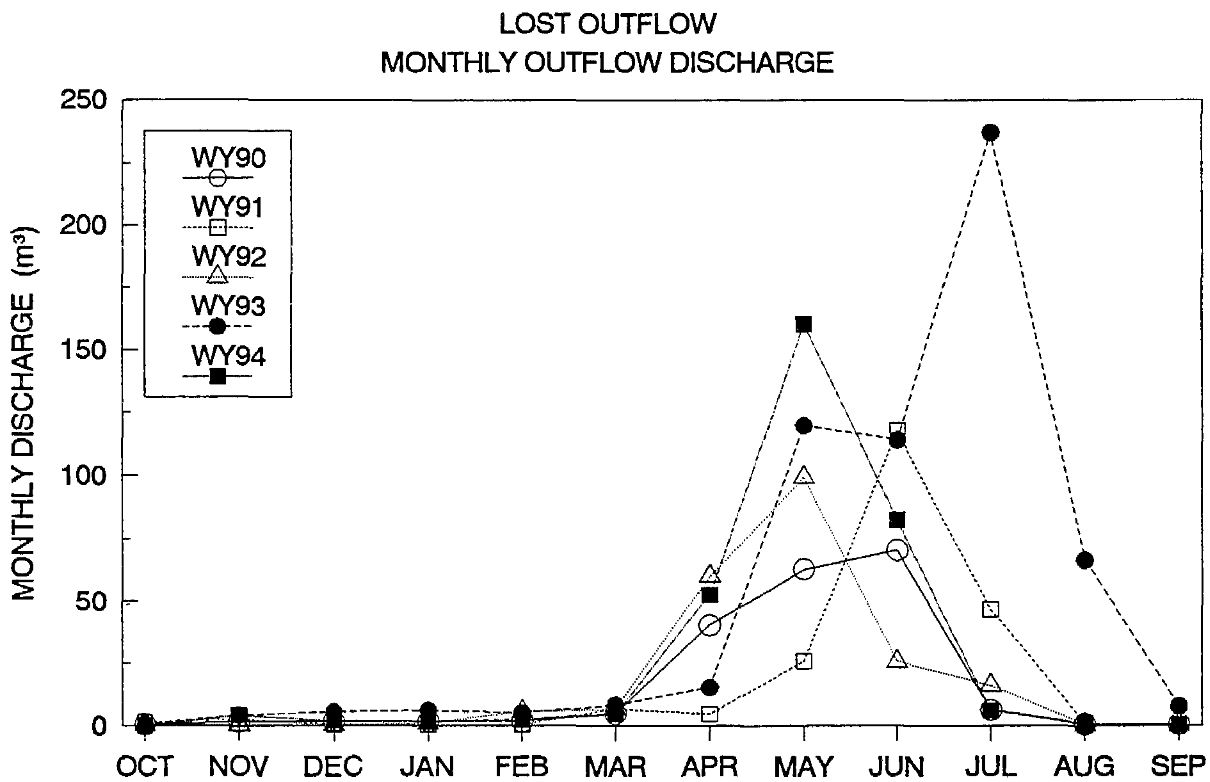

EMERALD OUTFLOW
FLOW-DURATION CURVE 1989-1994
DAILY RUNOFF (mm)
100
50
20
10
1
0.1
0.1
1
10
20
50
100
PERCENTAGE OF TIME DAILY RUNOFF IS EQUALED OR EXCEEDED
EMERALD OUTFLOW
RUNOFF FREQUENCY 1989-1994
FREQUENCY
700
600
500
400
300
200
100
0
0.01
0.1
1
5
10
20
30
50
100
DAILY RUNOFF (mm)

Figure II-19


LOST OUTFLOW
MONTHLY OUTFLOW DISCHARGE
MONTHLY DISCHARGE (m³)
WY90
WY91
WY92
WY93
WY94
0
50
100
150
200
250
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP

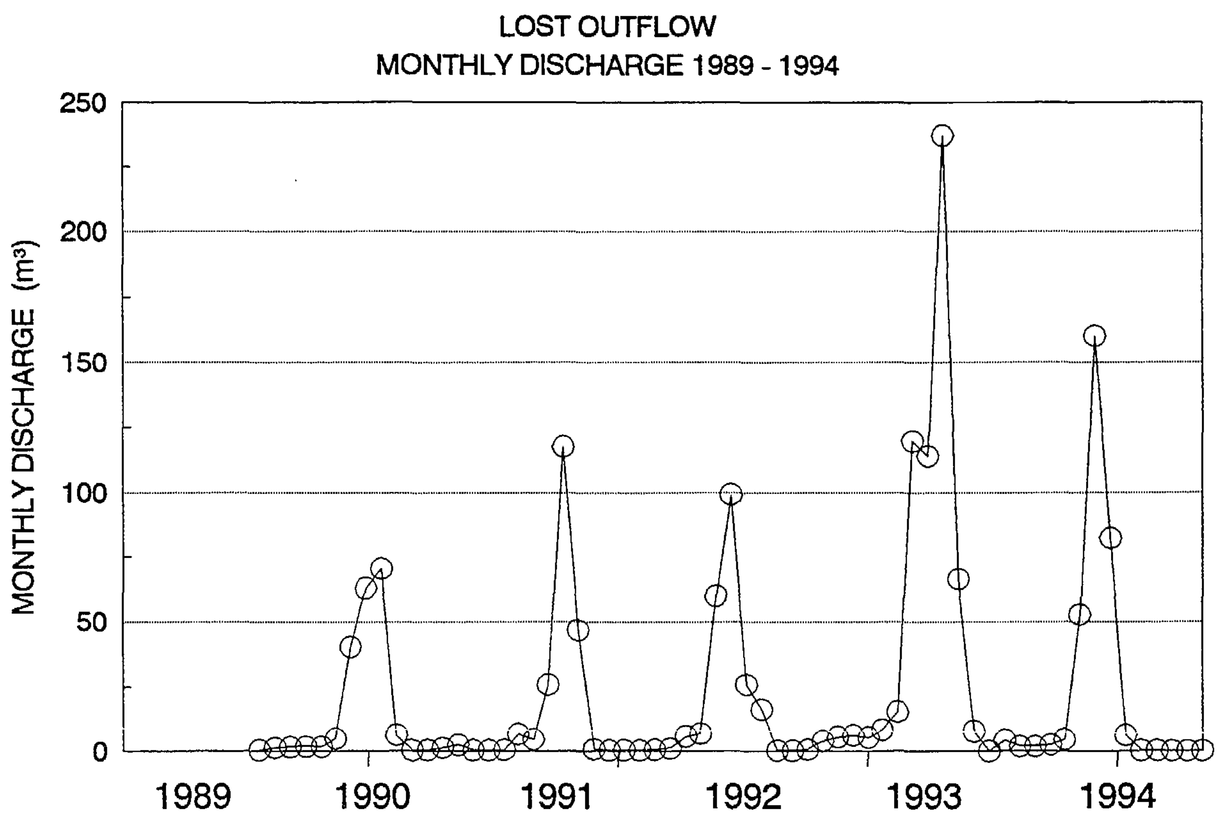
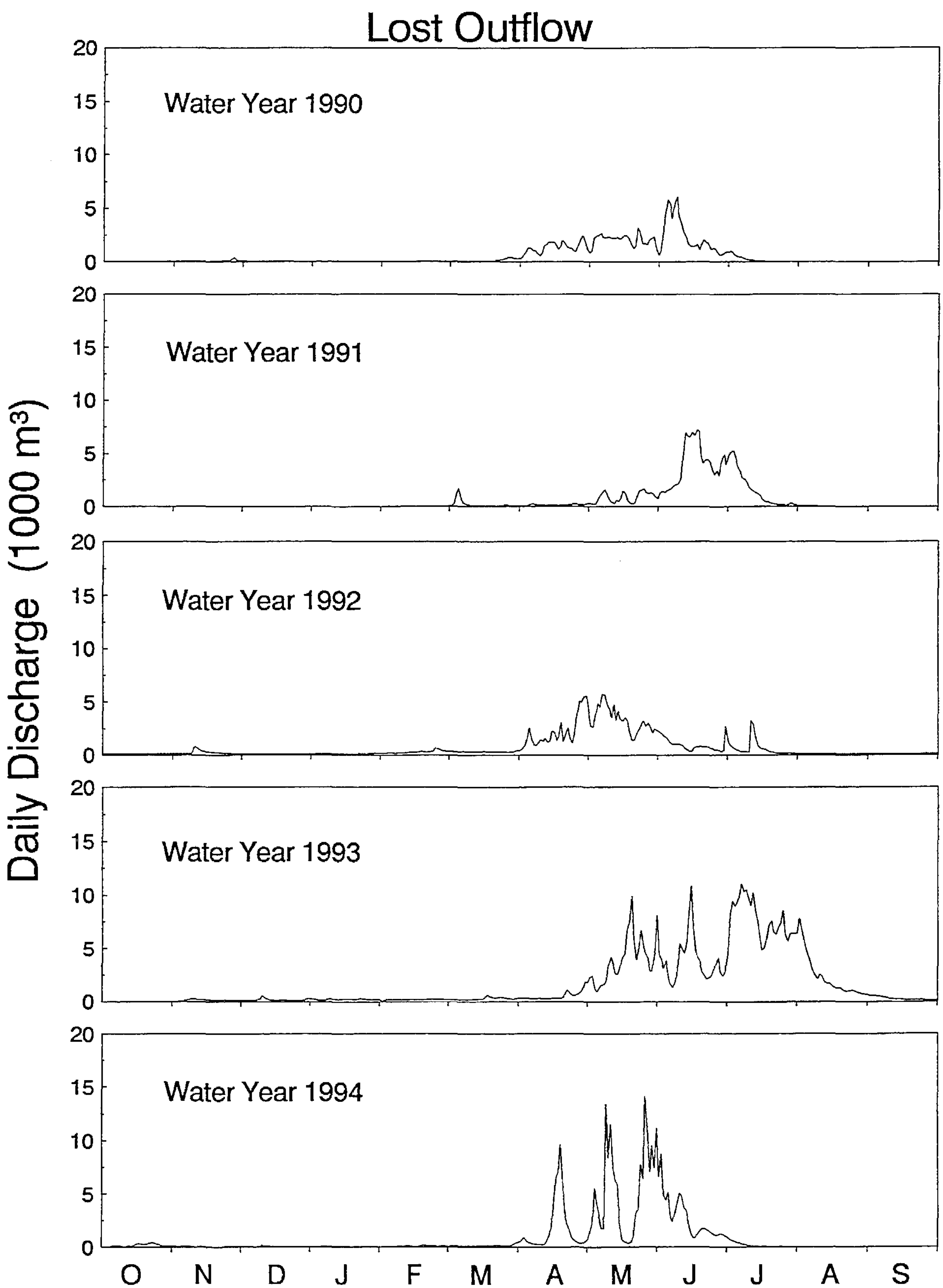
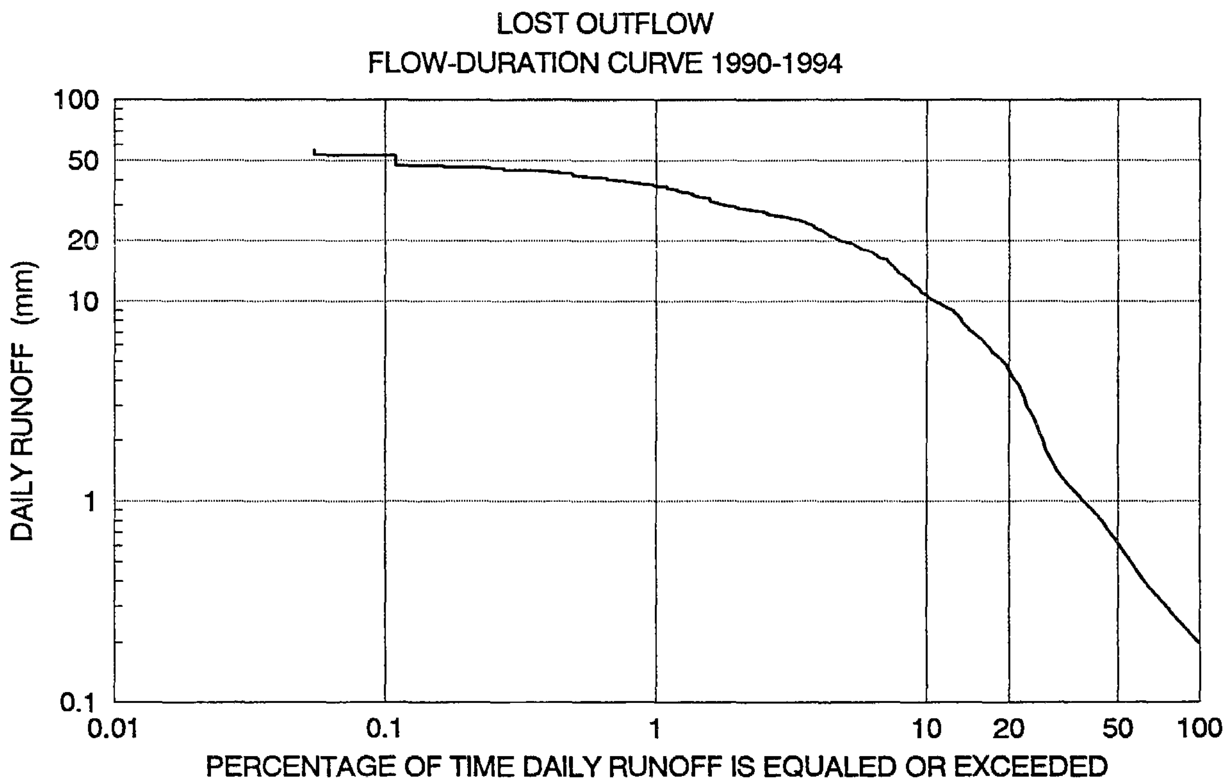

LOST OUTFLOW
MONTHLY DISCHARGE 1989 - 1994
MONTHLY DISCHARGE (m³)
0
50
100
150
200
250
1989
1990
1991
1992
1993
1994

Figure II-20

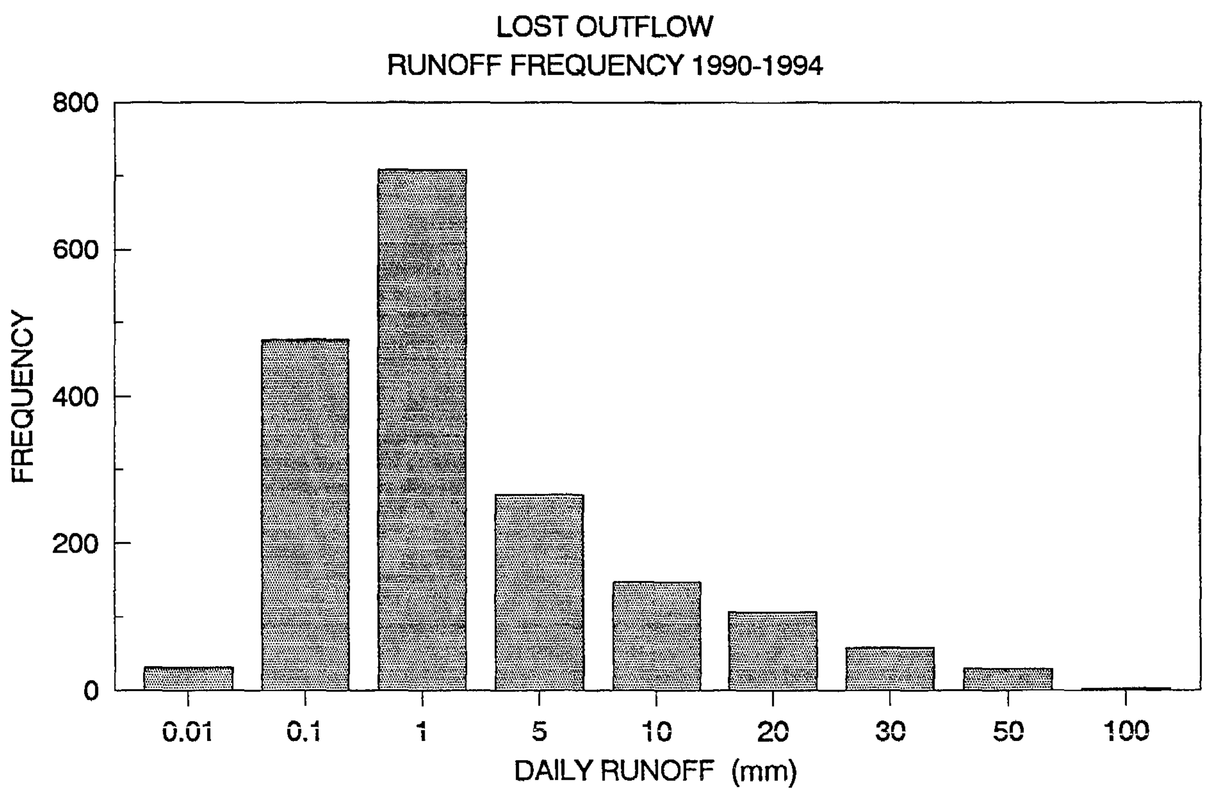


Lost Outflow
Daily Discharge (1000 m³)
Water Year 1990
Water Year 1991
Water Year 1992
Water Year 1993
Water Year 1994
20
15
10
5
0
O N D J F M A M J J A S

Figure II-21

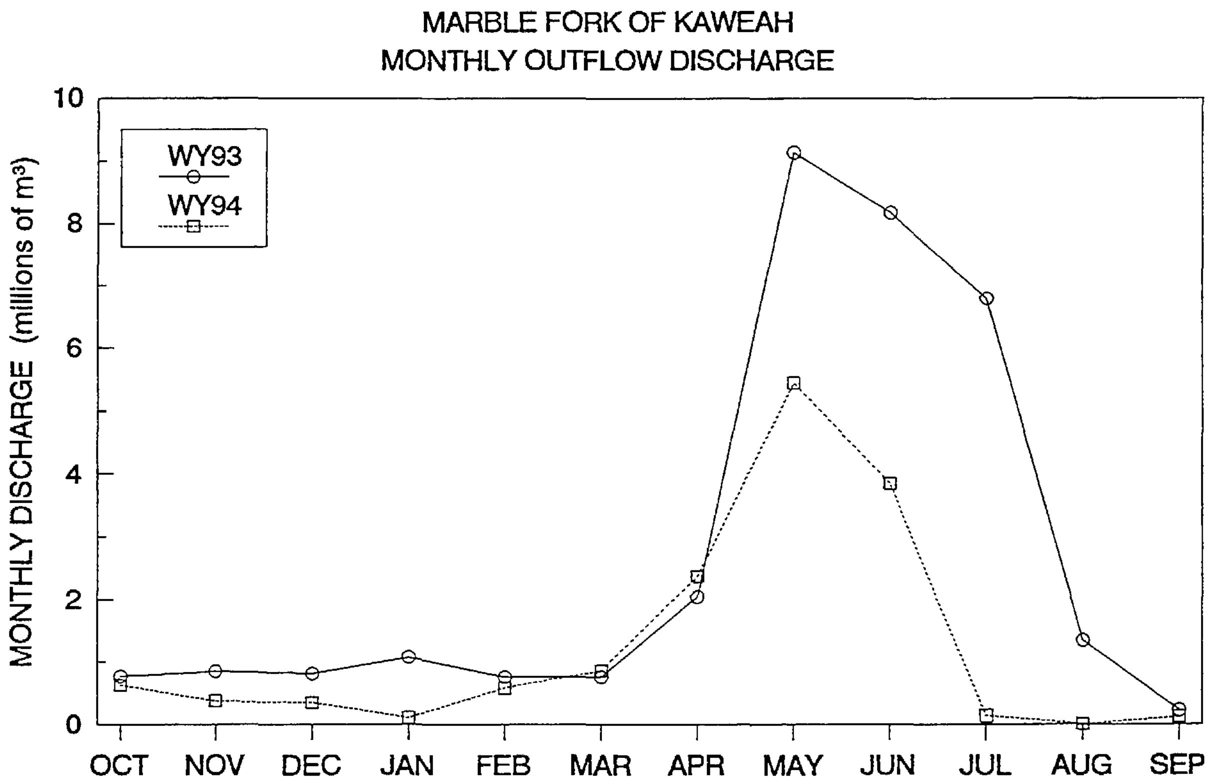


LOST OUTFLOW
FLOW-DURATION CURVE 1990-1994
DAILY RUNOFF (mm)
100
50
20
10
1
0.1
0.01
0.1
1
10
20
50
100
PERCENTAGE OF TIME DAILY RUNOFF IS EQUALED OR EXCEEDED



LOST OUTFLOW
RUNOFF FREQUENCY 1990-1994
FREQUENCY
800
600
400
200
0
0.01
0.1
1
5
10
20
30
50
100
DAILY RUNOFF (mm)

Figure II-22


MARBLE FORK OF KAWEAH
MONTHLY OUTFLOW DISCHARGE
MONTHLY DISCHARGE (millions of m³)
WY93
WY94
0
2
4
6
8
10
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP

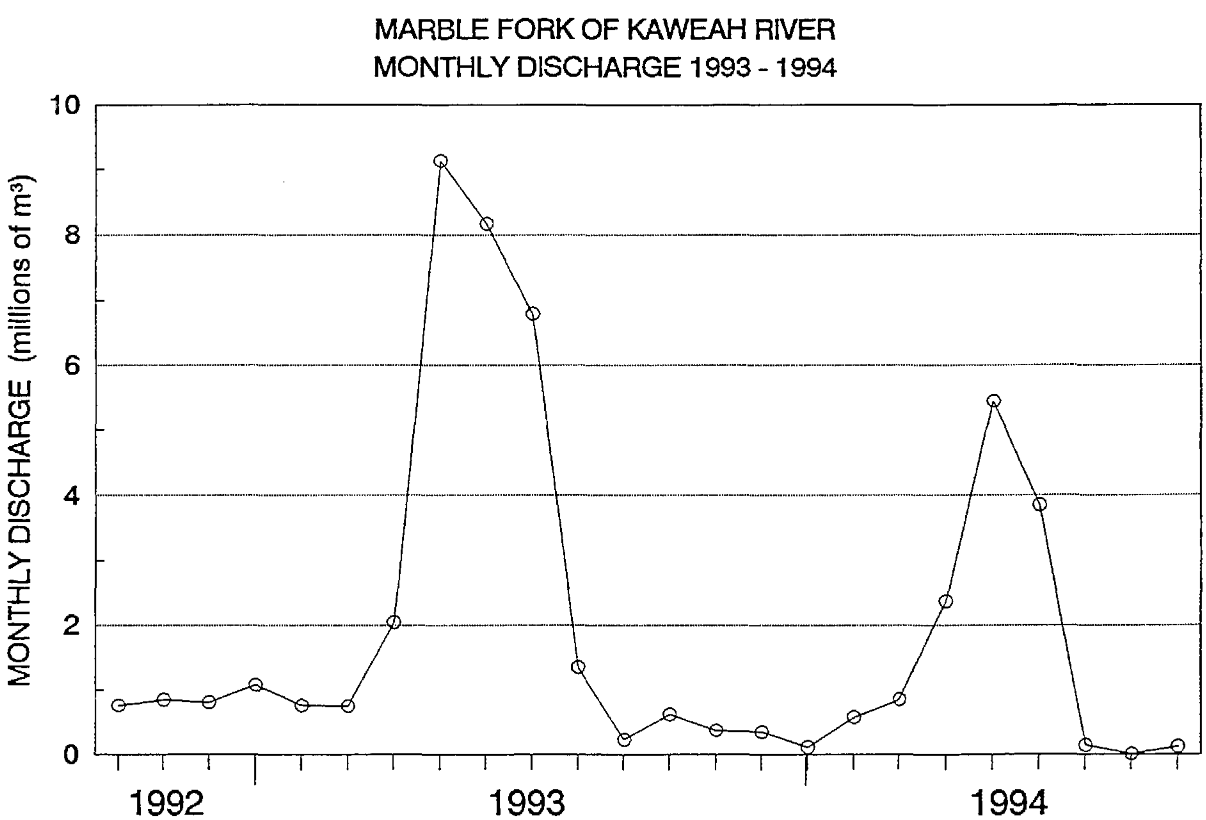
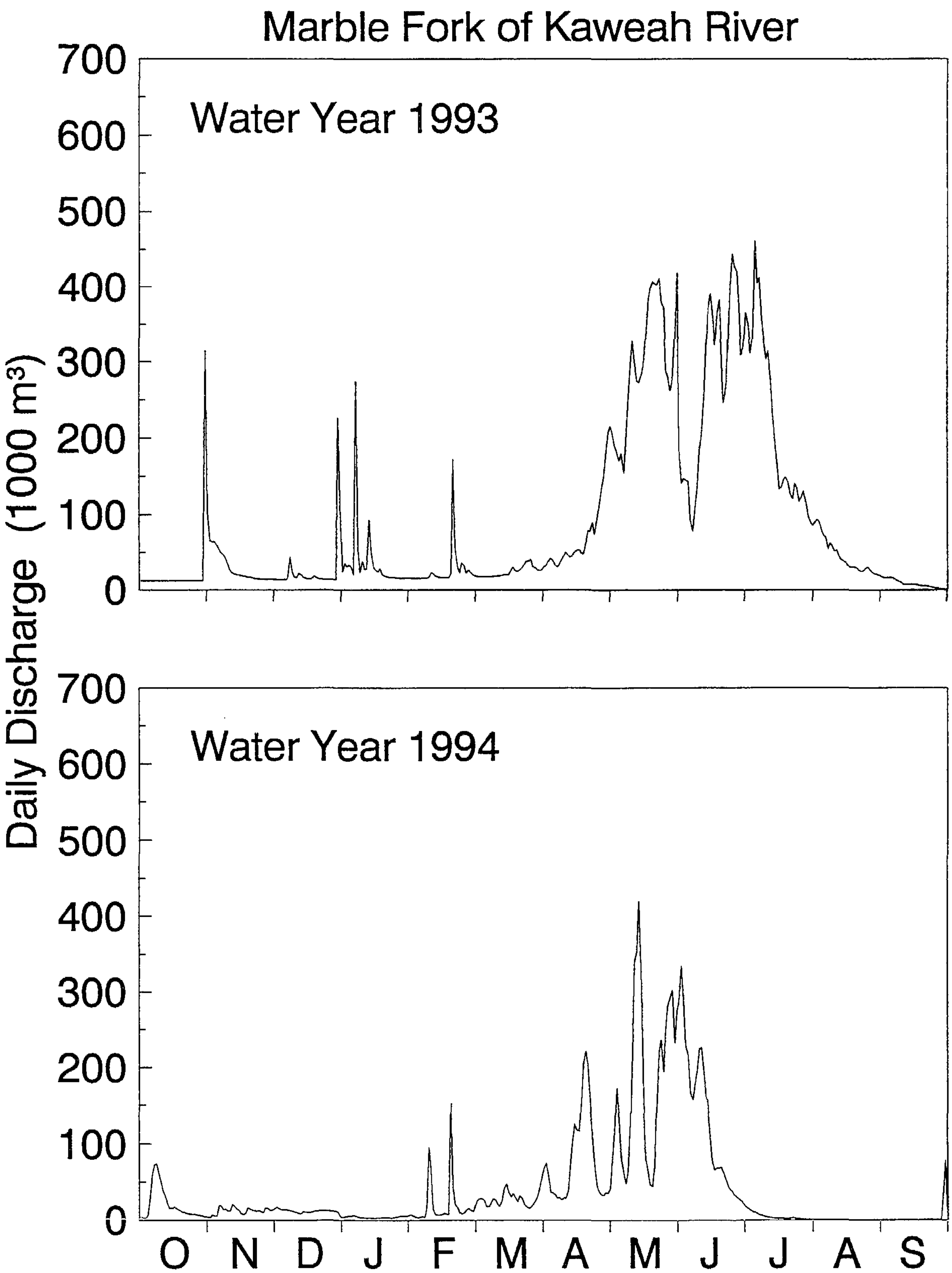
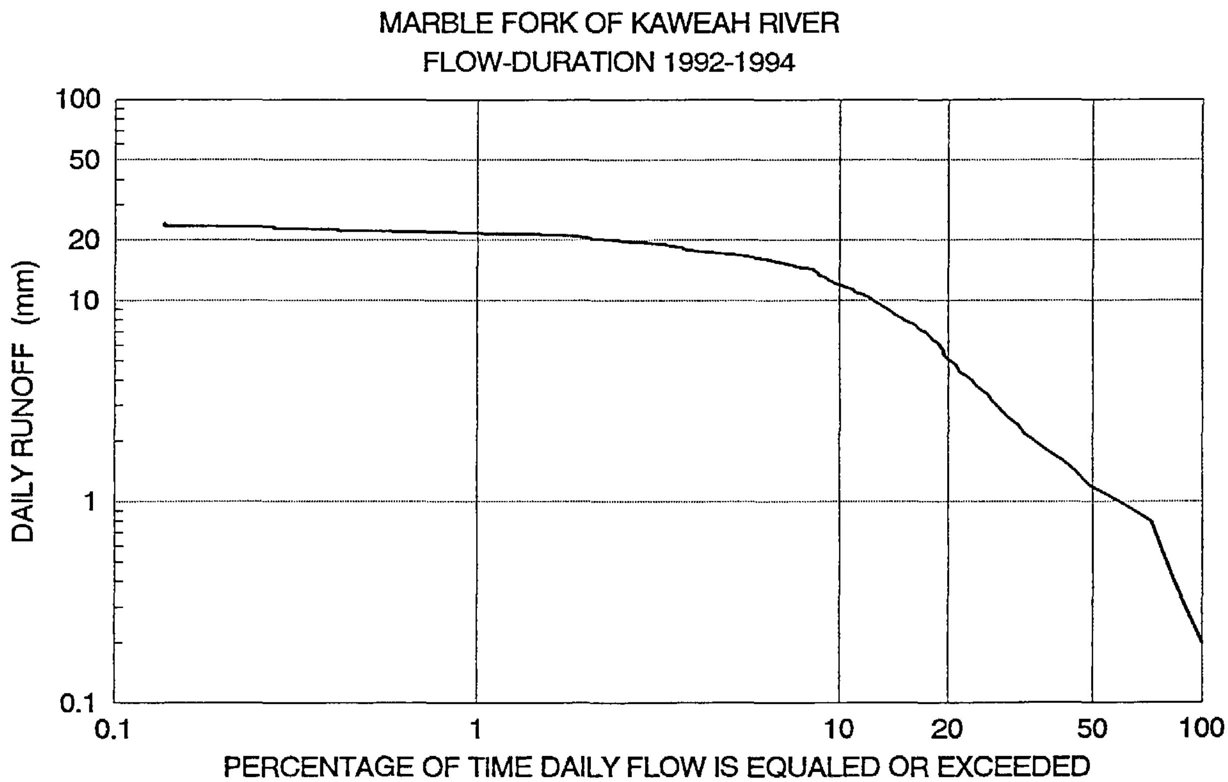

MARBLE FORK OF KAWEAH RIVER
MONTHLY DISCHARGE 1993 - 1994
MONTHLY DISCHARGE (millions of m³)
0
2
4
6
8
10
1992
1993
1994

Figure II-23



Marble Fork of Kaweah River
Water Year 1993
Water Year 1994
Daily Discharge (1000 m³)
700
600
500
400
300
200
100
0
O N D J F M A M J J A S

Figure II-24


MARBLE FORK OF KAWEAH RIVER
FLOW-DURATION 1992-1994
DAILY RUNOFF (mm)
100
50
20
10
1
0.1
0.1
1
10
20
50
100
PERCENTAGE OF TIME DAILY FLOW IS EQUALED OR EXCEEDED

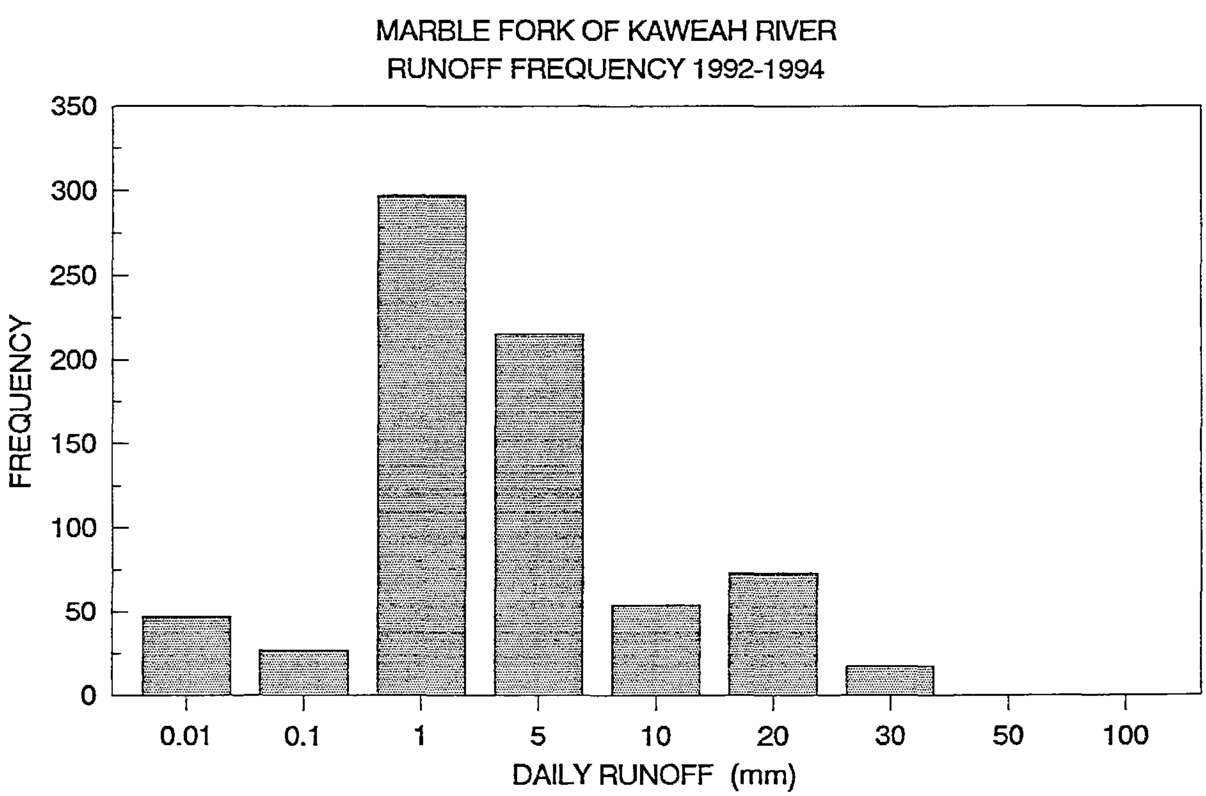
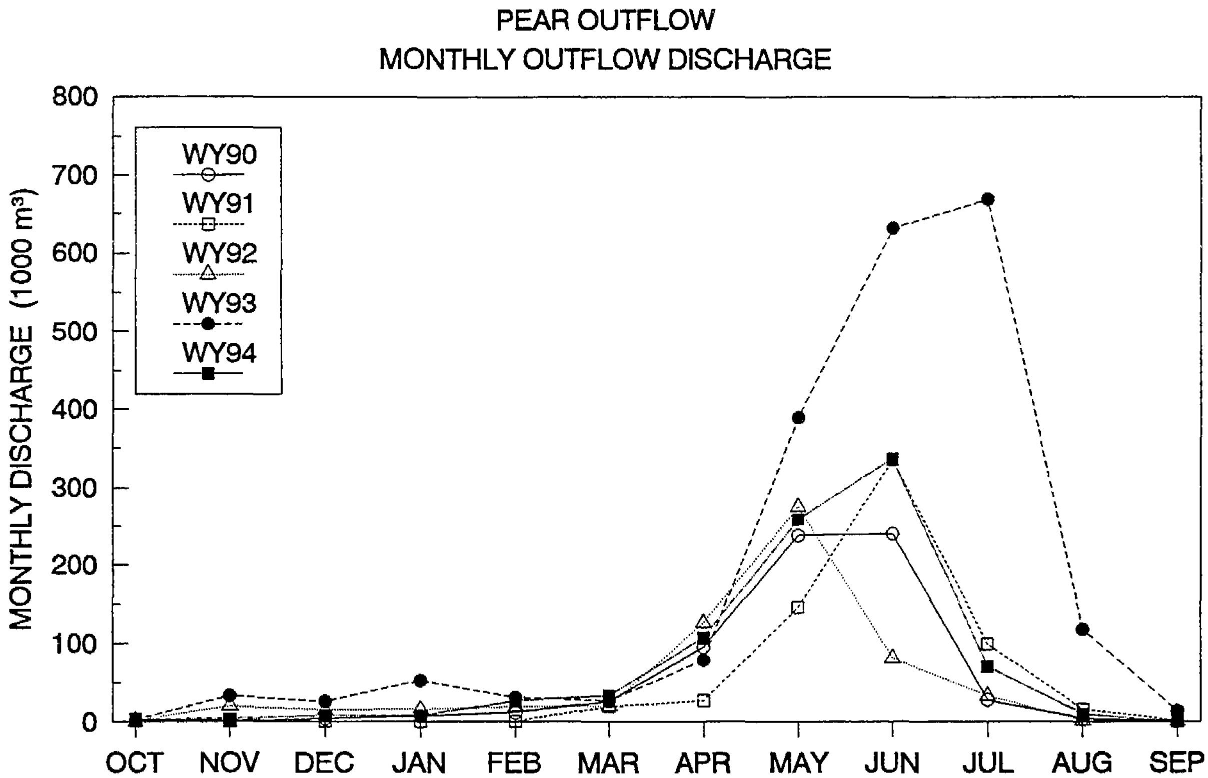

MARBLE FORK OF KAWEAH RIVER
RUNOFF FREQUENCY 1992-1994
FREQUENCY
350
300
250
200
150
100
50
0
0.01
0.1
1
5
10
20
30
50
100
DAILY RUNOFF (mm)

Figure II-25


PEAR OUTFLOW
MONTHLY OUTFLOW DISCHARGE
MONTHLY DISCHARGE (1000 m³)
WY90
WY91
WY92
WY93
WY94
800
700
600
500
400
300
200
100
0
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP

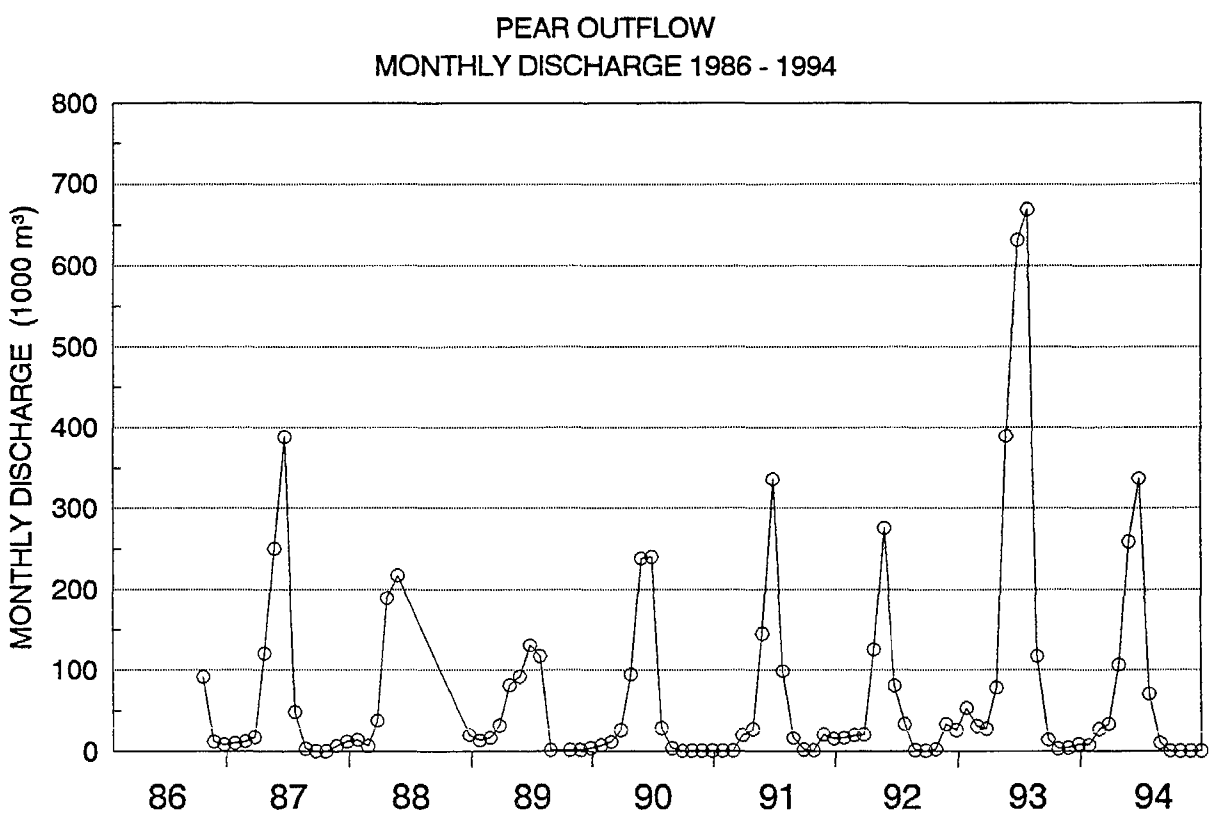
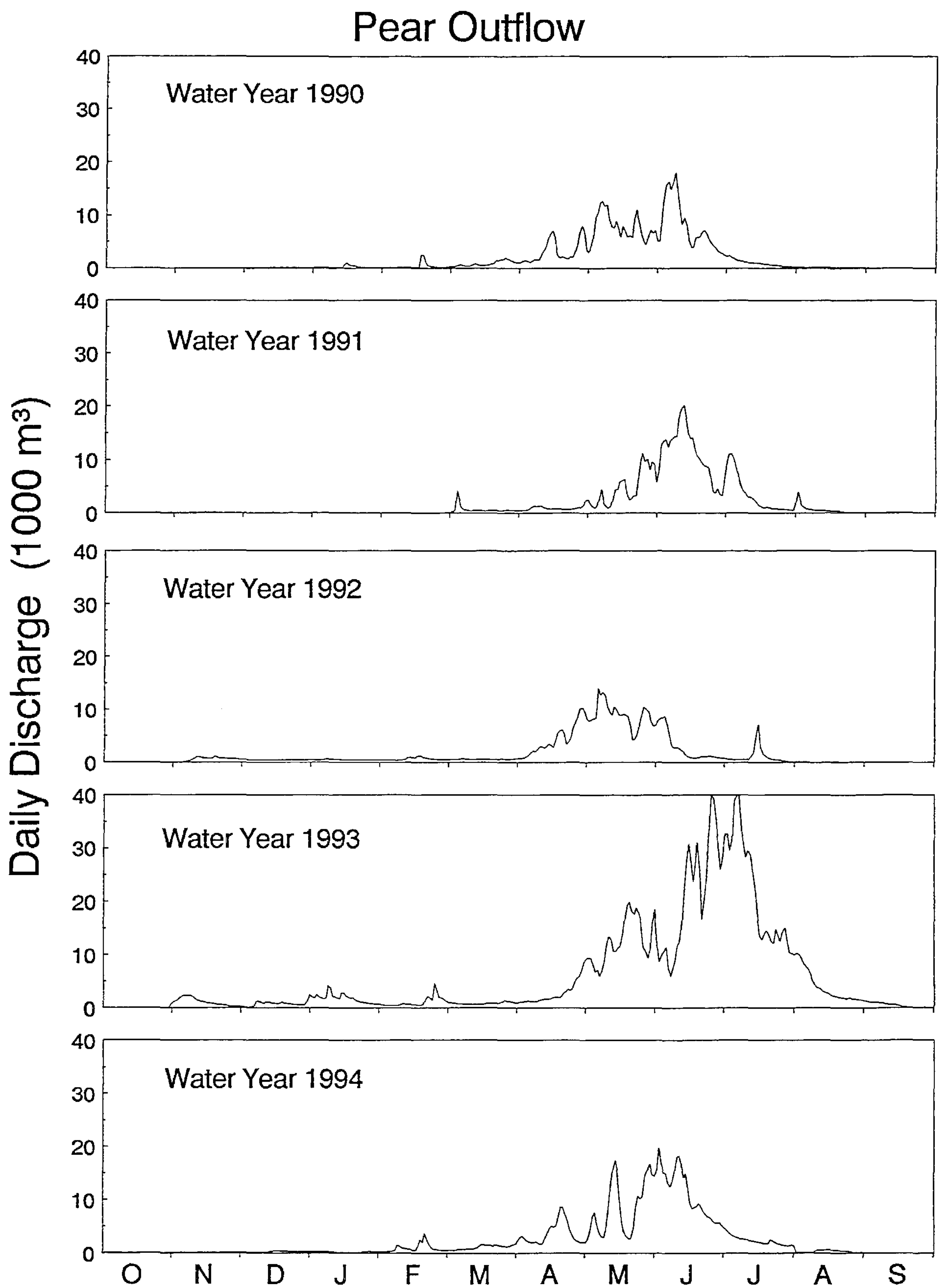

PEAR OUTFLOW
MONTHLY DISCHARGE 1986 - 1994
MONTHLY DISCHARGE (1000 m³)
800
700
600
500
400
300
200
100
0
86
87
88
89
90
91
92
93
94

Figure II-26



Pear Outflow
Daily Discharge (1000 m³)
Water Year 1990
Water Year 1991
Water Year 1992
Water Year 1993
Water Year 1994
40
30
20
10
0
O
N
D
J
F
M
A
M
J
J
A
S

Figure II-27

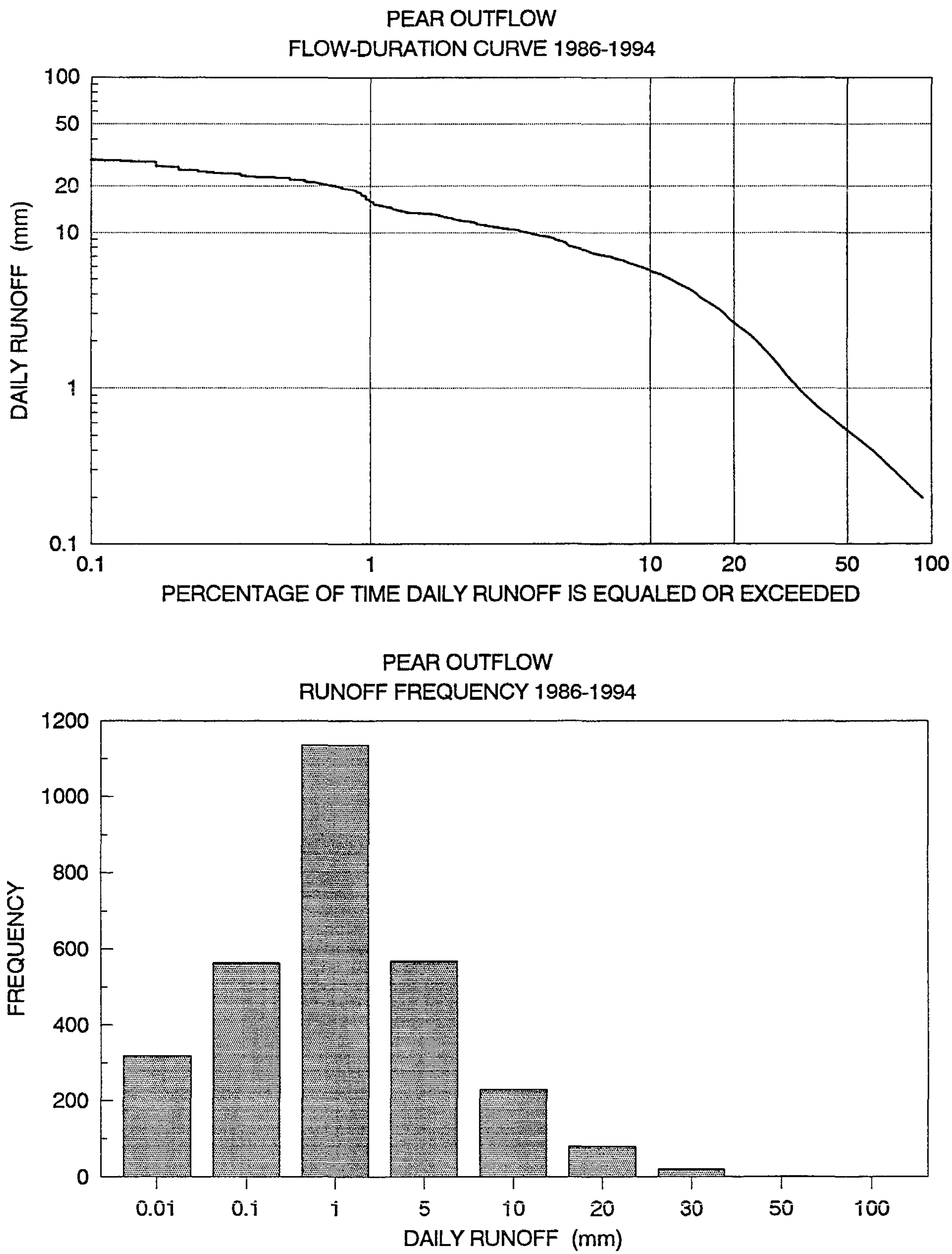
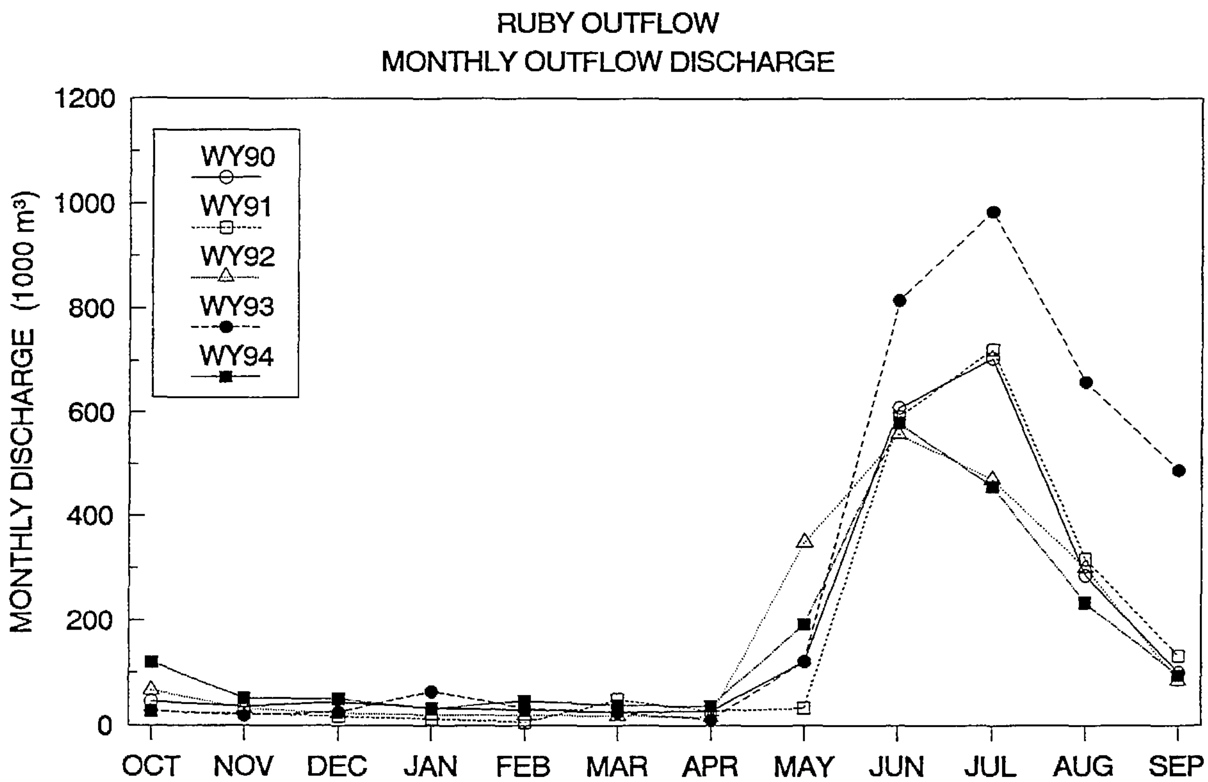
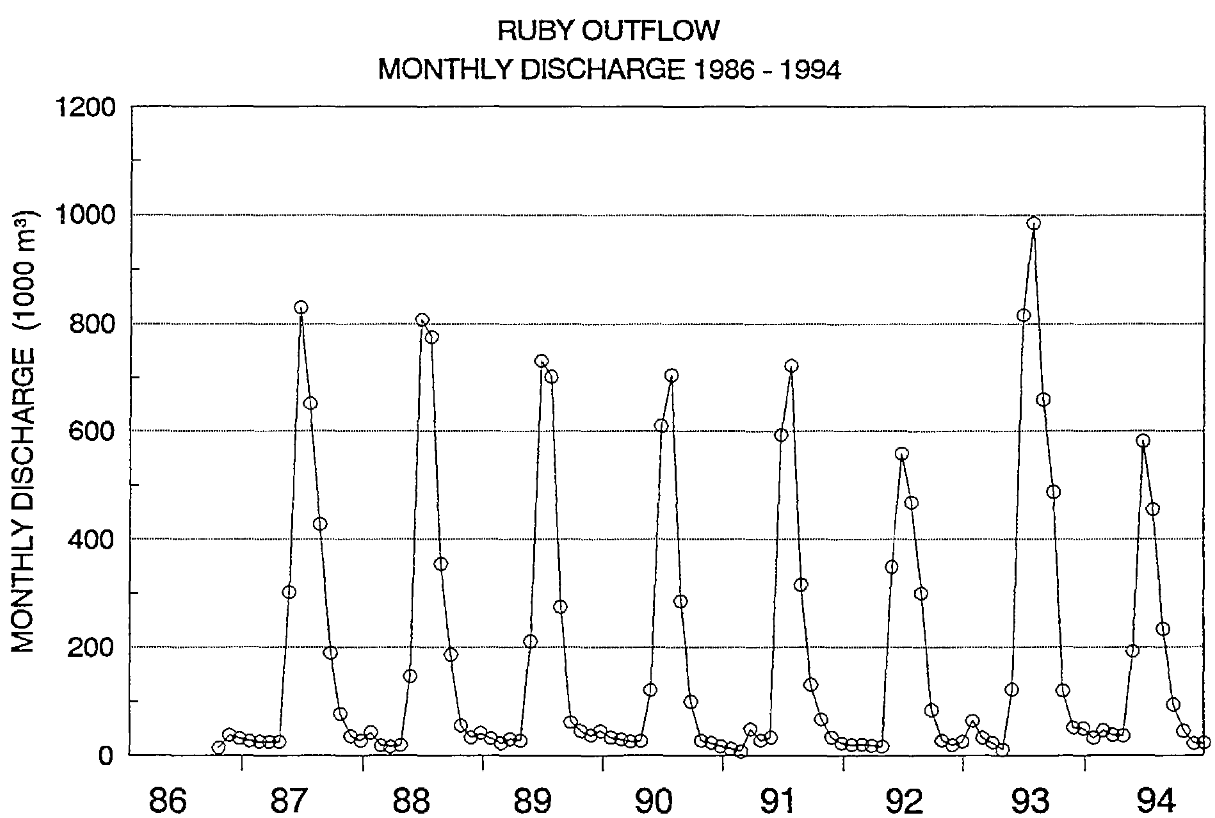

PEAR OUTFLOW
FLOW-DURATION CURVE 1986-1994
DAILY RUNOFF (mm)
100
50
20
10
1
0.1
0.1
1
10
20
50
100
PERCENTAGE OF TIME DAILY RUNOFF IS EQUALED OR EXCEEDED
PEAR OUTFLOW
RUNOFF FREQUENCY 1986-1994
FREQUENCY
1200
1000
800
600
400
200
0
0.01
0.1
1
5
10
20
30
50
100
DAILY RUNOFF (mm)

Figure II-28

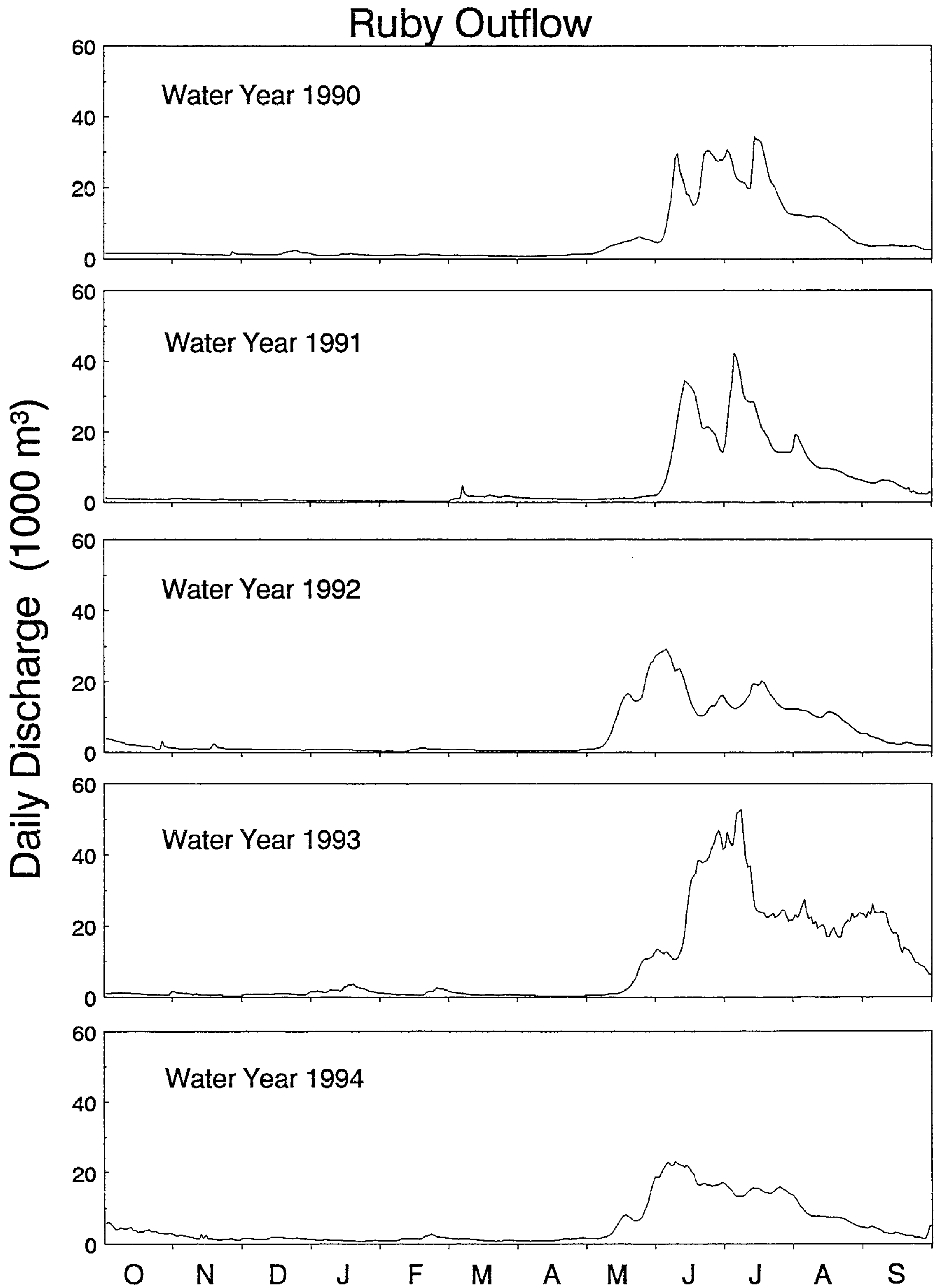


RUBY OUTFLOW
MONTHLY OUTFLOW DISCHARGE
MONTHLY DISCHARGE (1000 m³)
WY90
WY91
WY92
WY93
WY94
0
200
400
600
800
1000
1200
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP



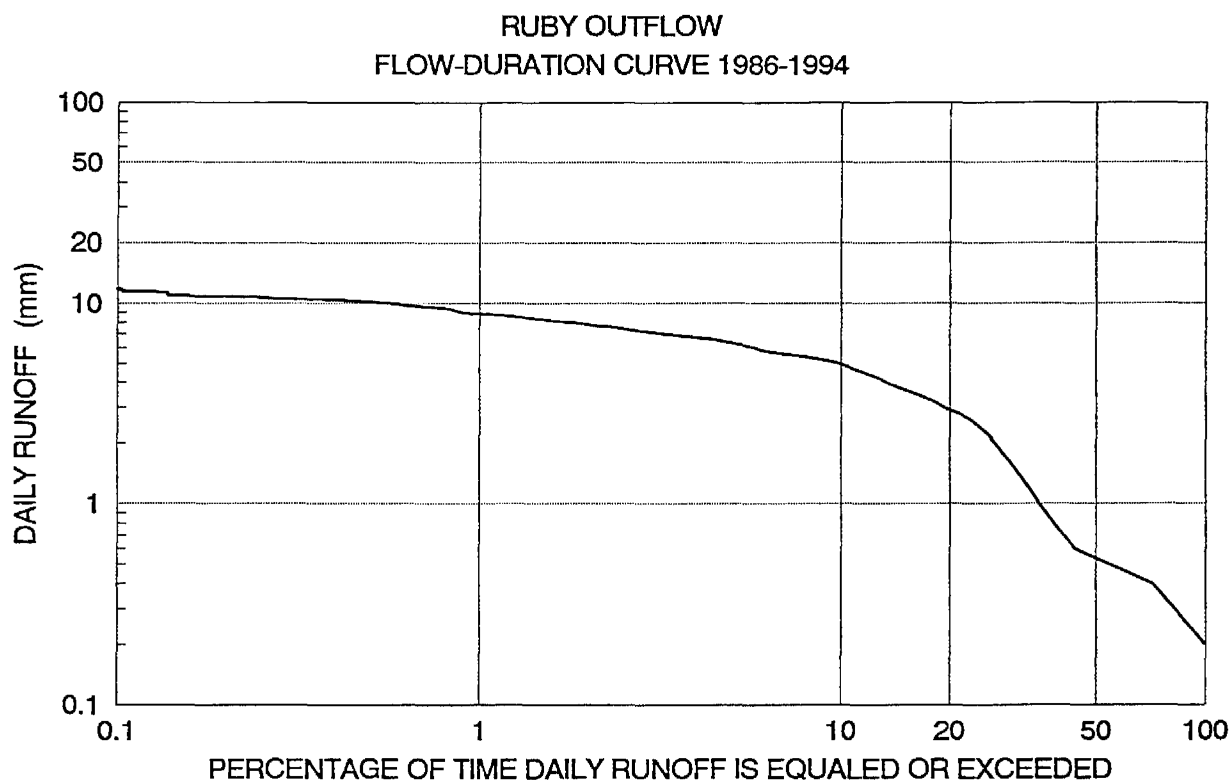
RUBY OUTFLOW
MONTHLY DISCHARGE 1986 - 1994
MONTHLY DISCHARGE (1000 m³)
0
200
400
600
800
1000
1200
86
87
88
89
90
91
92
93
94

Figure II-29



Ruby Outflow
Daily Discharge (1000 m³)
Water Year 1990
Water Year 1991
Water Year 1992
Water Year 1993
Water Year 1994
0
20
40
60
O N D J F M A M J J A S

Figure II-30


RUBY OUTFLOW
FLOW-DURATION CURVE 1986-1994
DAILY RUNOFF (mm)
100
50
20
10
1
0.1
0.1
1
10
20
50
100
PERCENTAGE OF TIME DAILY RUNOFF IS EQUALED OR EXCEEDED

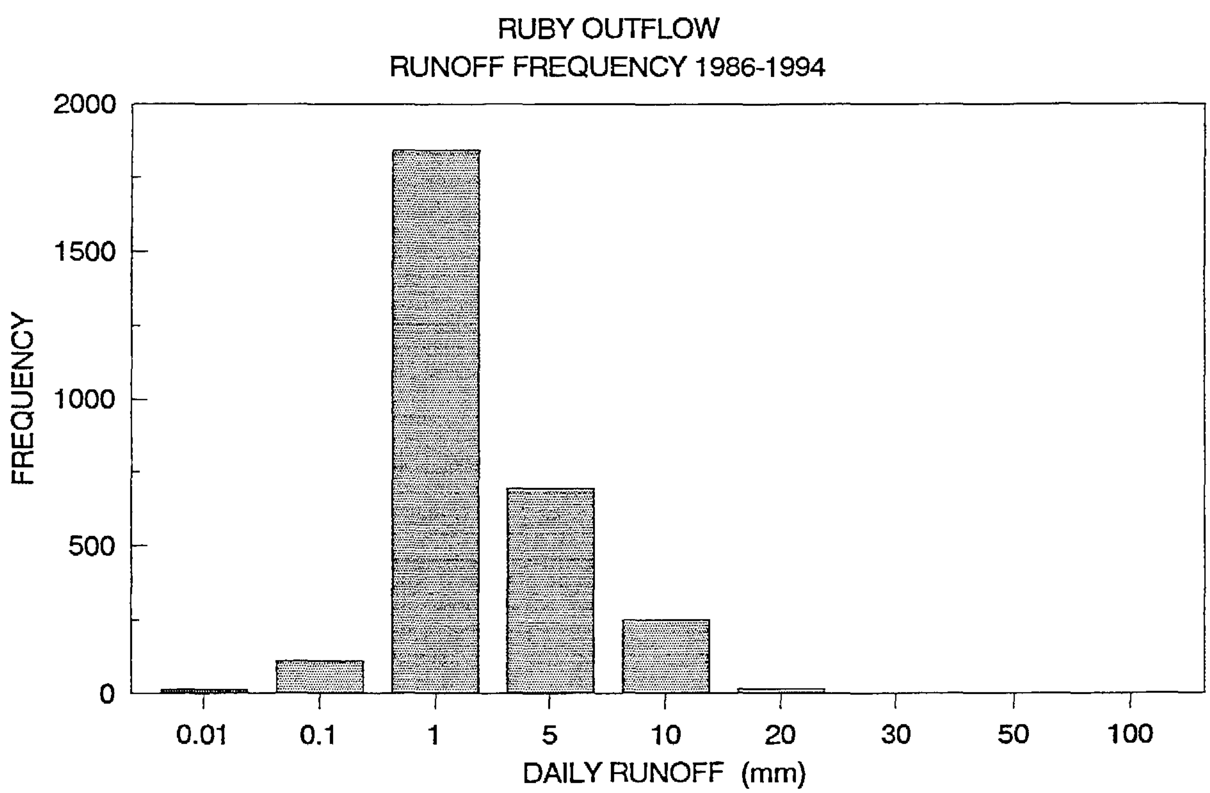
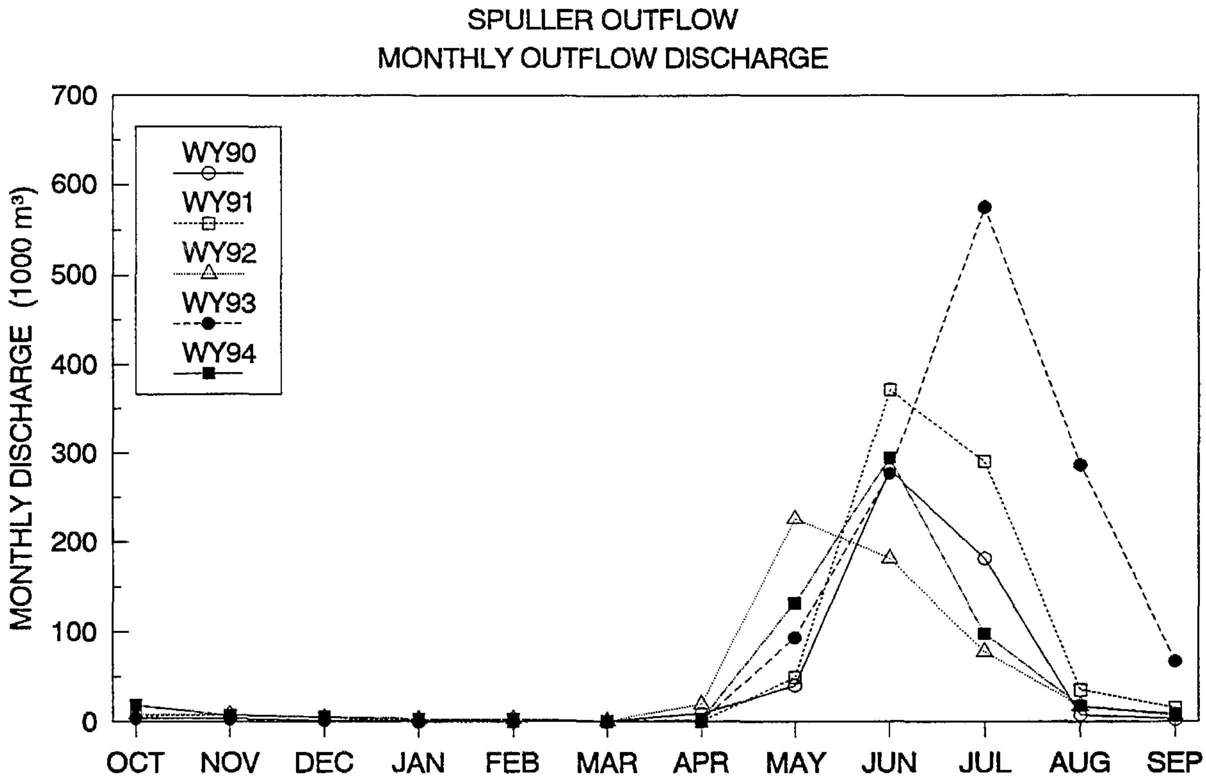

RUBY OUTFLOW
RUNOFF FREQUENCY 1986-1994
FREQUENCY
2000
1500
1000
500
0
0.01
0.1
1
5
10
20
30
50
100
DAILY RUNOFF (mm)

Figure II-31


SPULLER OUTFLOW
MONTHLY OUTFLOW DISCHARGE
MONTHLY DISCHARGE (1000 m³)
700
600
500
400
300
200
100
0
WY90
WY91
WY92
WY93
WY94
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP

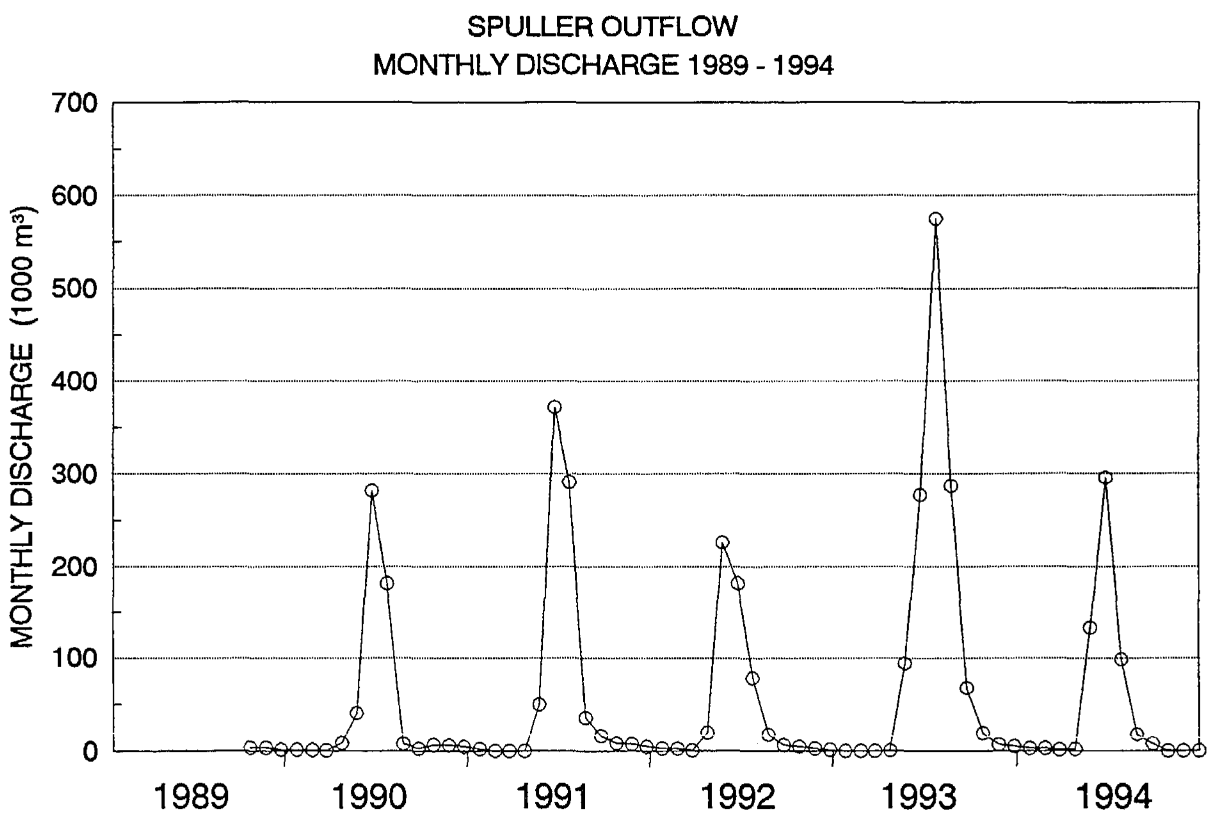
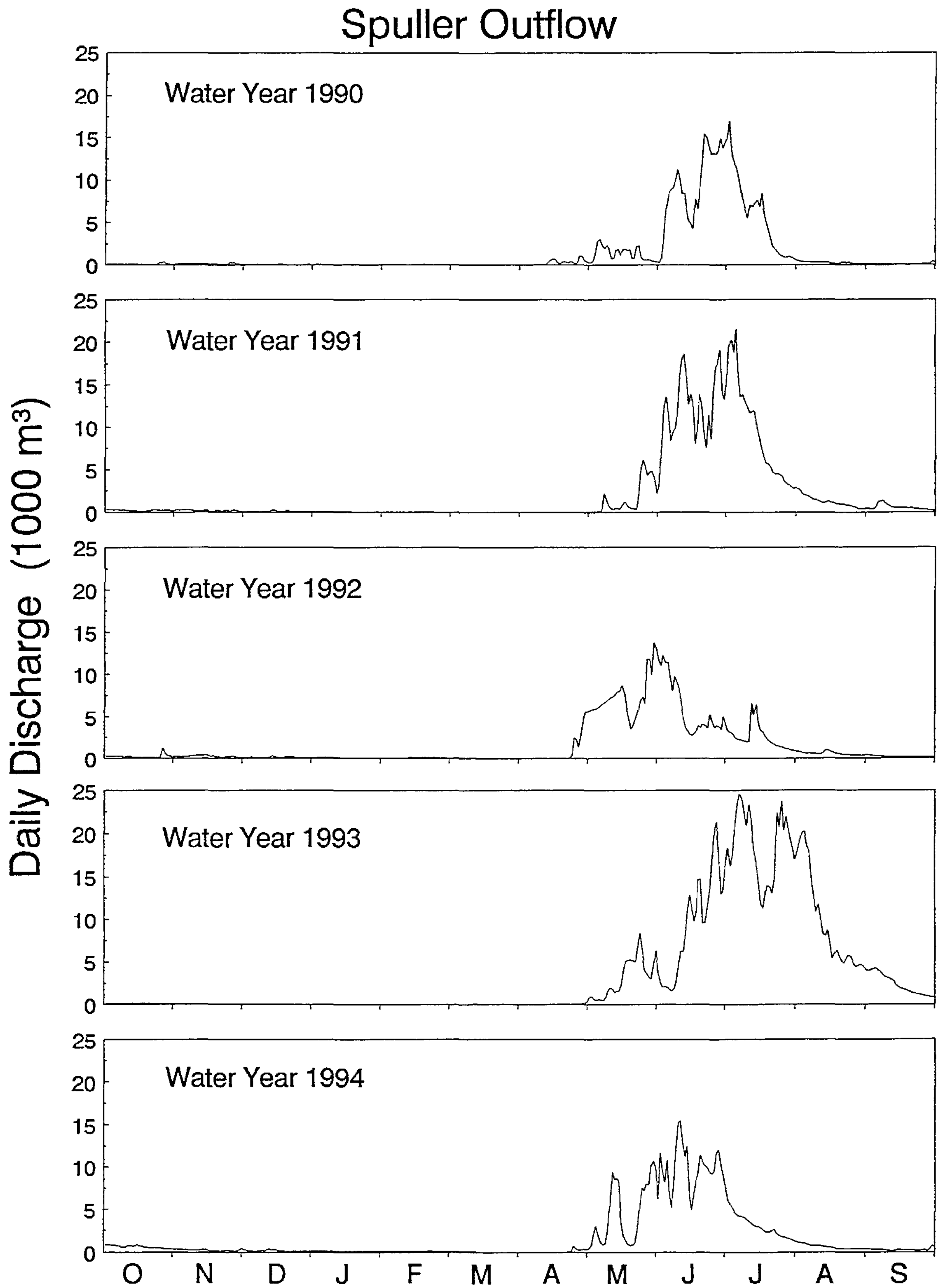
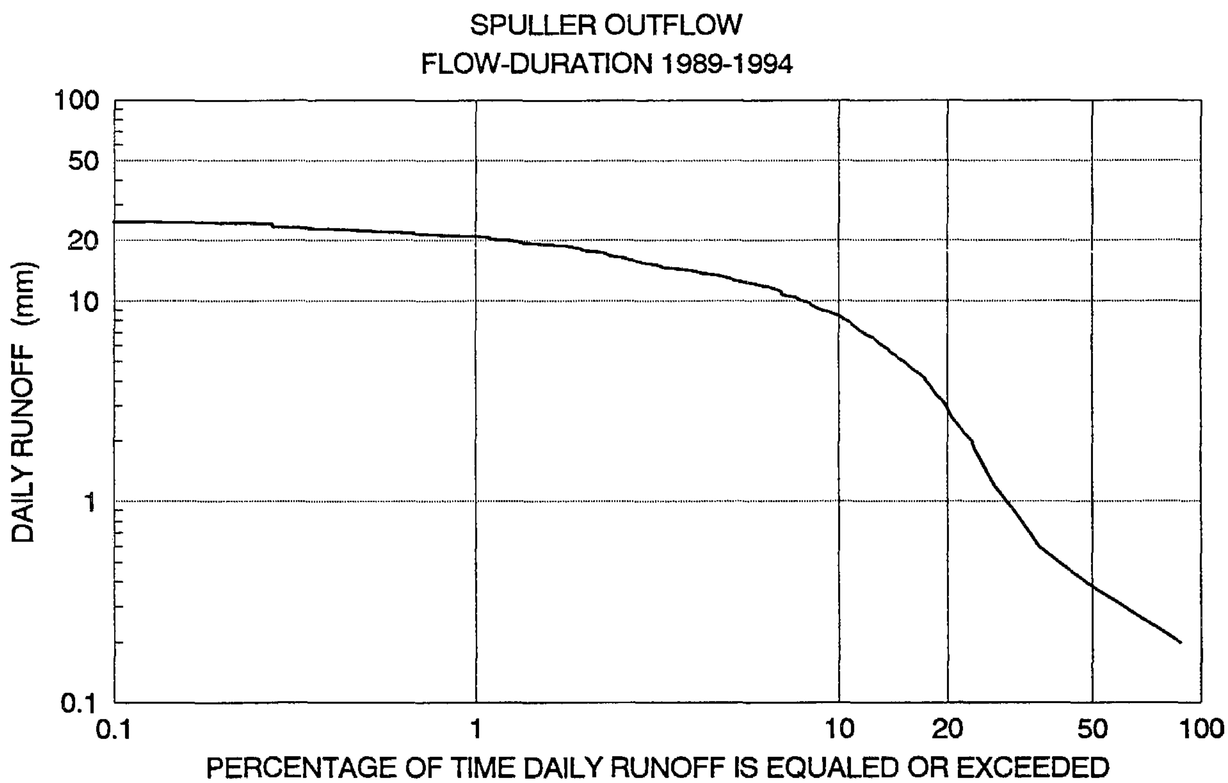

SPULLER OUTFLOW
MONTHLY DISCHARGE 1989 - 1994
MONTHLY DISCHARGE (1000 m³)
700
600
500
400
300
200
100
0
1989
1990
1991
1992
1993
1994

Figure II-32



Spuller Outflow
Daily Discharge (1000 m³)
Water Year 1990
Water Year 1991
Water Year 1992
Water Year 1993
Water Year 1994
25
20
15
10
5
0
O
N
D
J
F
M
A
M
J
J
A
S

Figure II-33


SPULLER OUTFLOW
FLOW-DURATION 1989-1994
100
50
20
10
1
0.1
DAILY RUNOFF (mm)
0.1
1
10
20
50
100
PERCENTAGE OF TIME DAILY RUNOFF IS EQUALED OR EXCEEDED

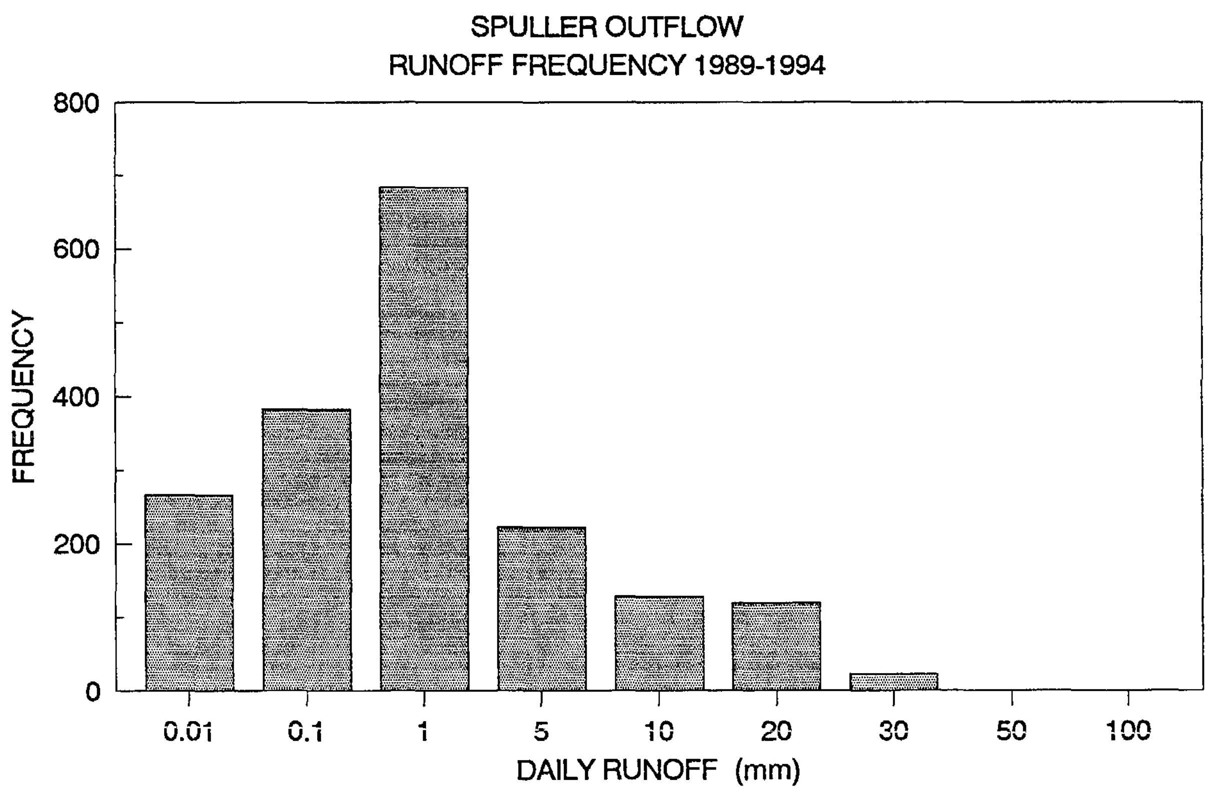
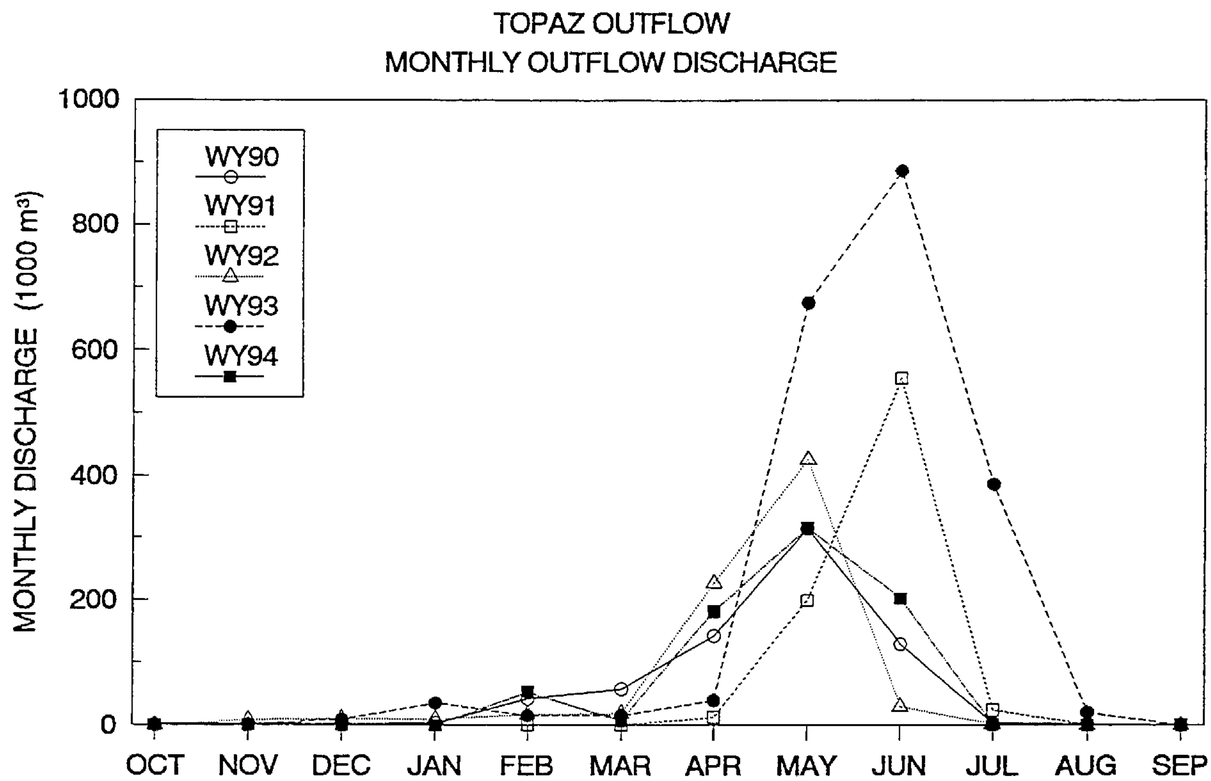

SPULLER OUTFLOW
RUNOFF FREQUENCY 1989-1994
800
600
400
200
0
FREQUENCY
0.01
0.1
1
5
10
20
30
50
100
DAILY RUNOFF (mm)

Figure II-34


TOPAZ OUTFLOW
MONTHLY OUTFLOW DISCHARGE
MONTHLY DISCHARGE (1000 m³)
WY90
WY91
WY92
WY93
WY94
0
200
400
600
800
1000
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP

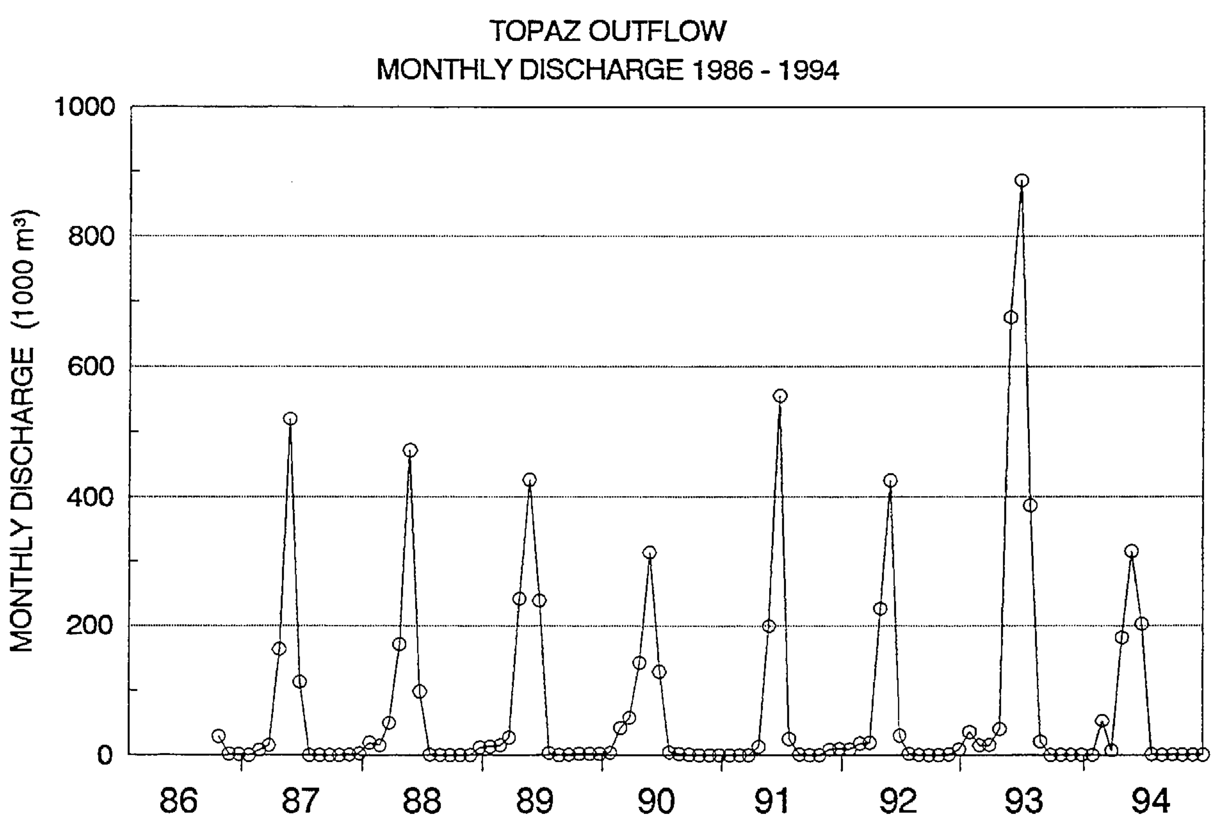
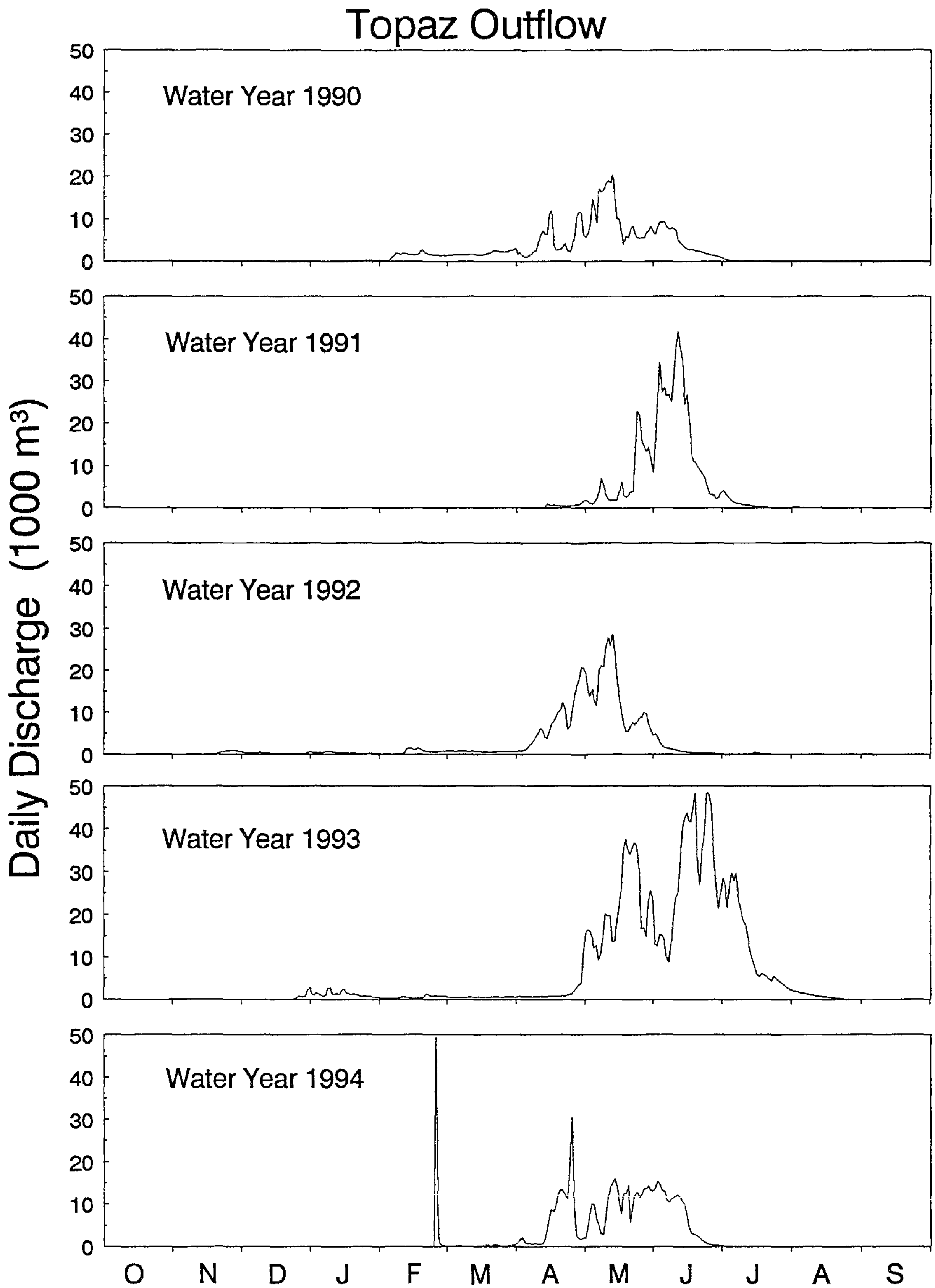

TOPAZ OUTFLOW
MONTHLY DISCHARGE 1986 - 1994
MONTHLY DISCHARGE (1000 m³)
0
200
400
600
800
1000
86
87
88
89
90
91
92
93
94

Figure II-35


Topaz Outflow
Daily Discharge (1000 m³)
Water Year 1990
Water Year 1991
Water Year 1992
Water Year 1993
Water Year 1994
50
40
30
20
10
0
O
N
D
J
F
M
A
M
J
J
A
S
Figure II-36

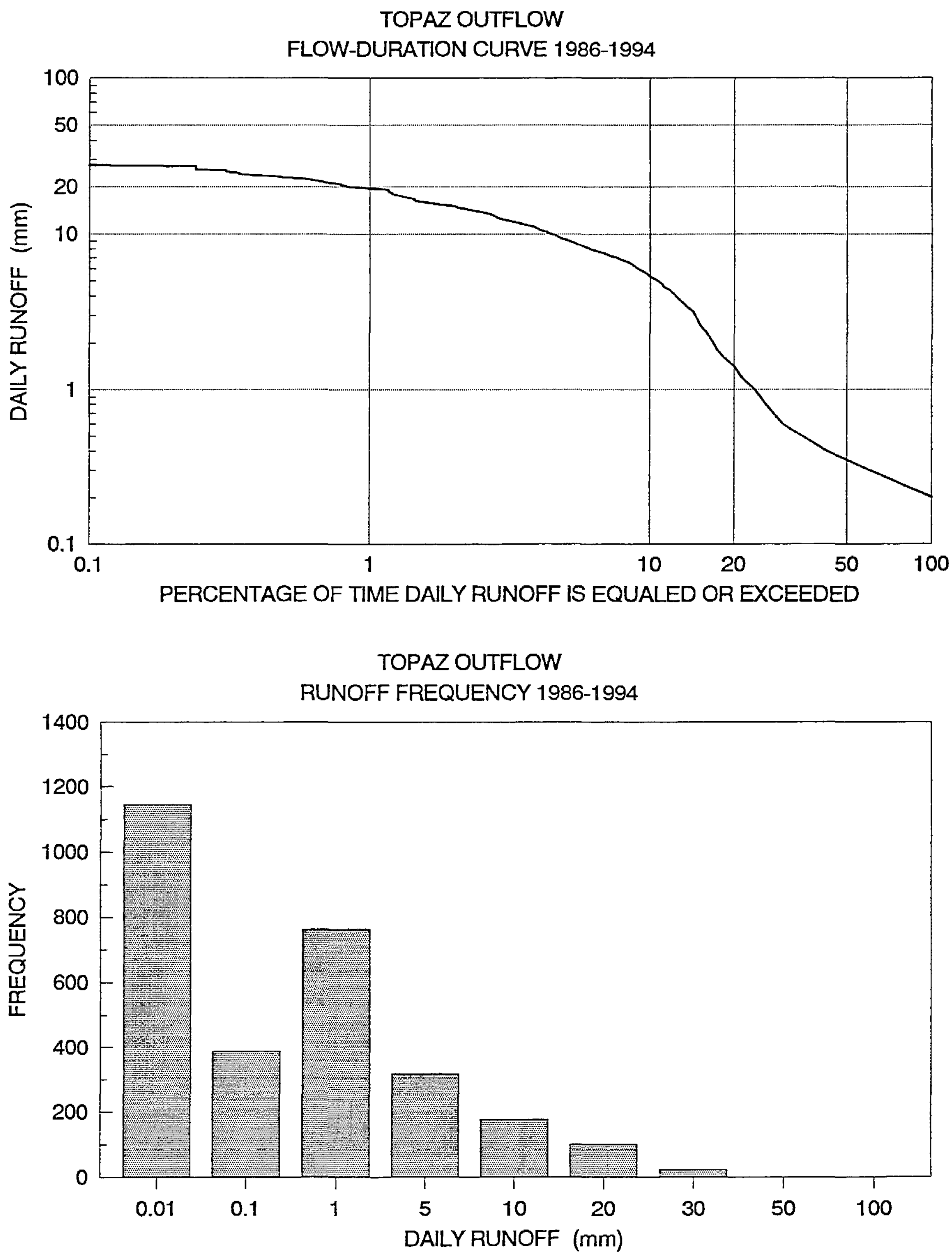
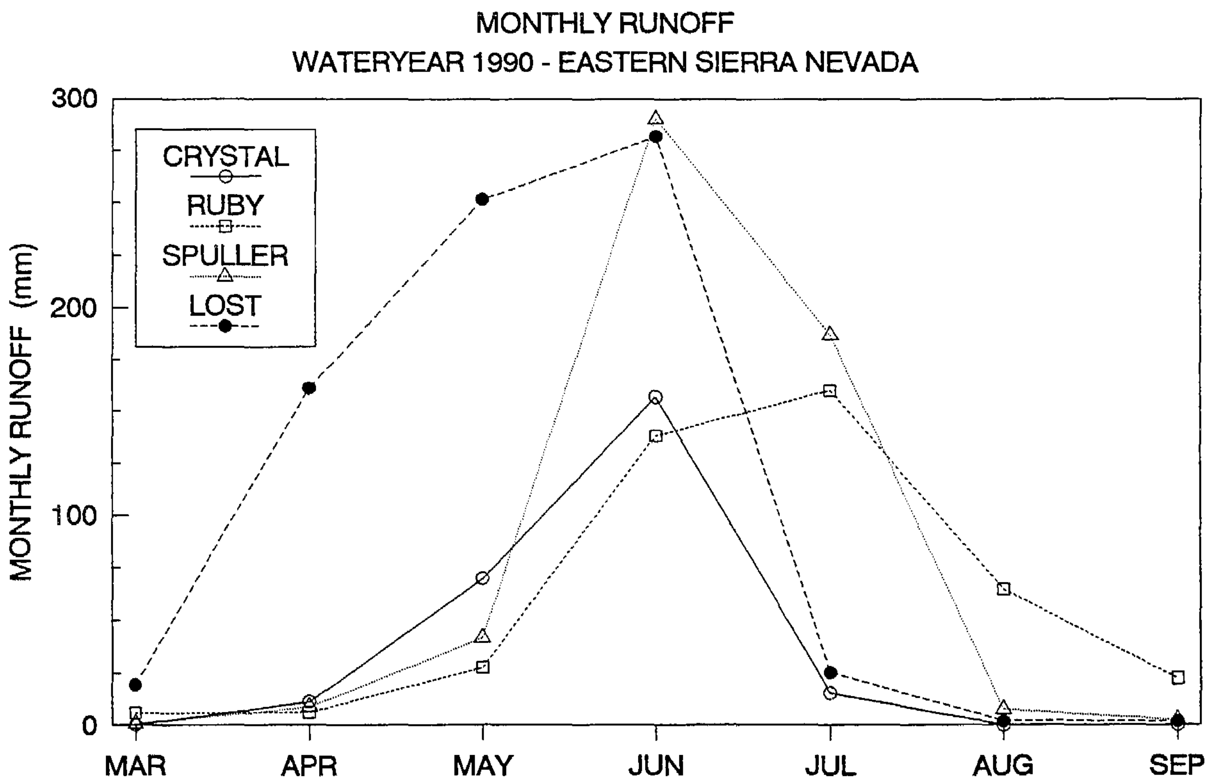

TOPAZ OUTFLOW
FLOW-DURATION CURVE 1986-1994
DAILY RUNOFF (mm)
100
50
20
10
1
0.1
0.1
1
10
20
50
100
PERCENTAGE OF TIME DAILY RUNOFF IS EQUALED OR EXCEEDED
TOPAZ OUTFLOW
RUNOFF FREQUENCY 1986-1994
FREQUENCY
1400
1200
1000
800
600
400
200
0
0.01
0.1
1
5
10
20
30
50
100
DAILY RUNOFF (mm)

Figure II-37


MONTHLY RUNOFF
WATERYEAR 1990 - EASTERN SIERRA NEVADA
CRYSTAL
RUBY
SPULLER
LOST
MONTHLY RUNOFF (mm)
300
200
100
0
MAR
APR
MAY
JUN
JUL
AUG
SEP

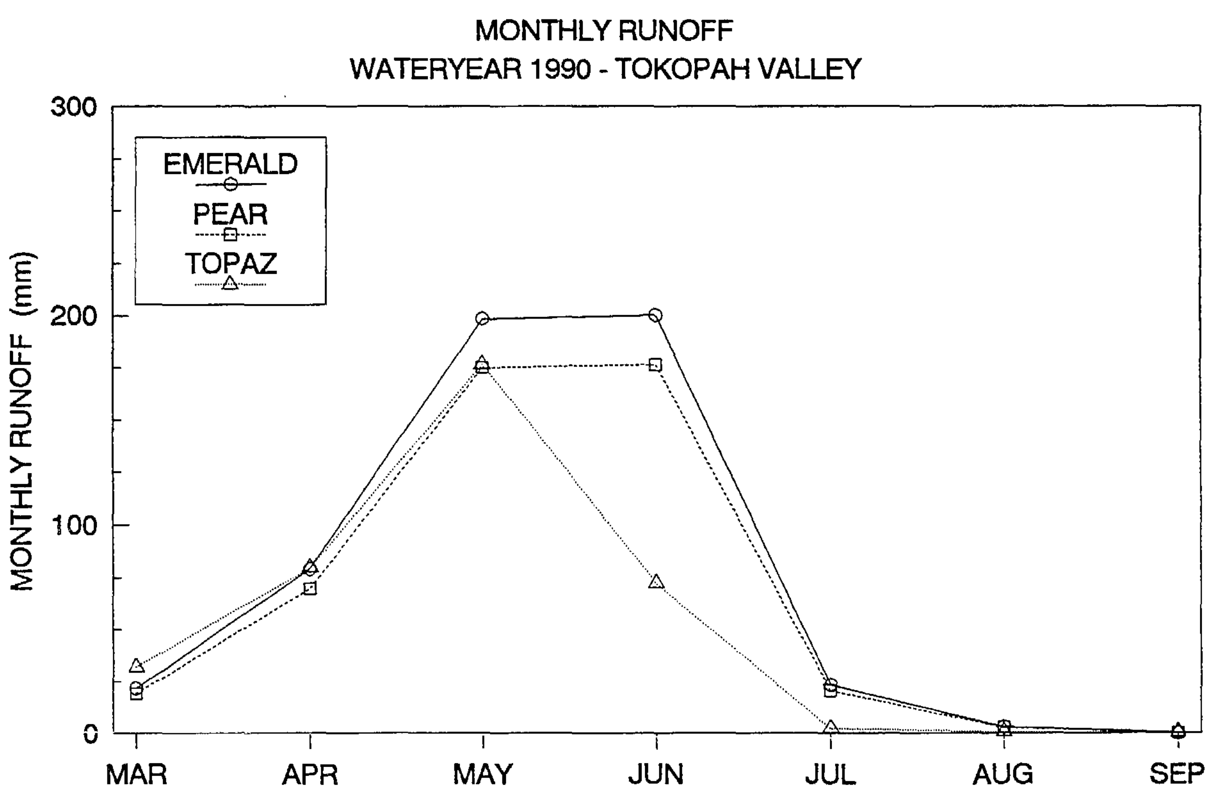
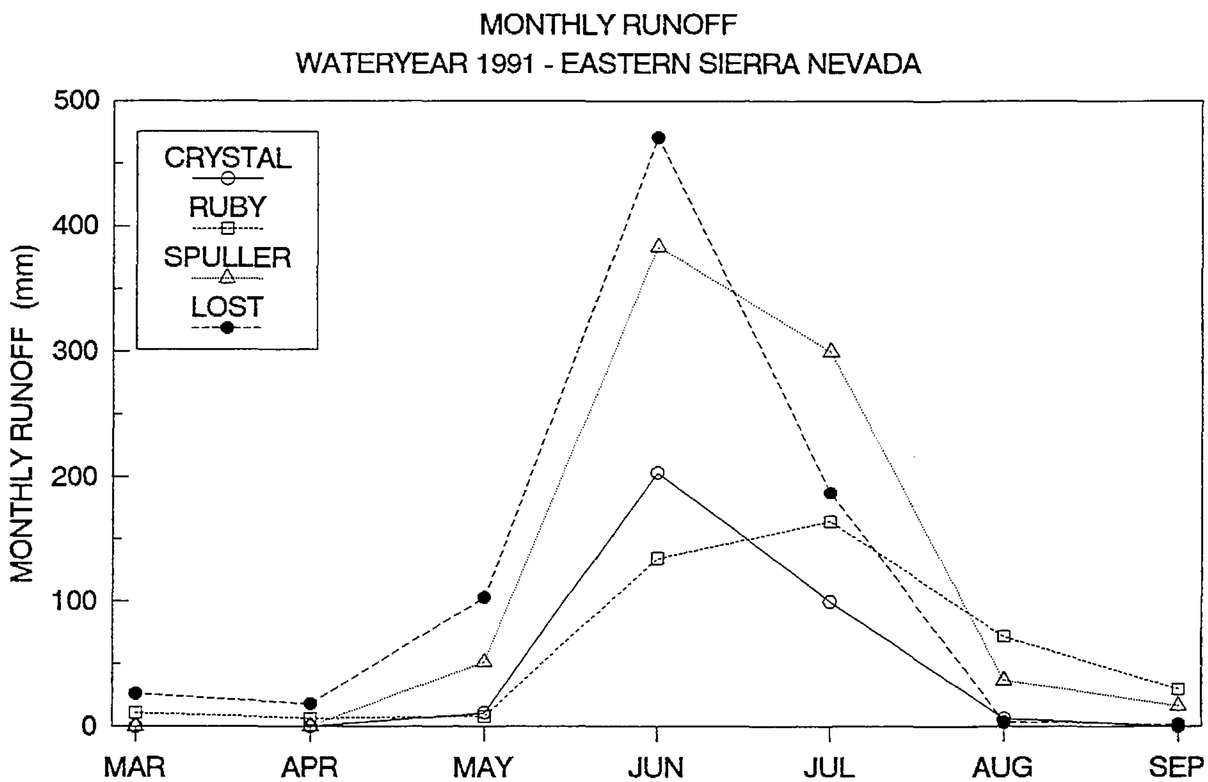

MONTHLY RUNOFF
WATERYEAR 1990 - TOKOPAH VALLEY
EMERALD
PEAR
TOPAZ
MONTHLY RUNOFF (mm)
300
200
100
0
MAR
APR
MAY
JUN
JUL
AUG
SEP

Figure II-38


MONTHLY RUNOFF
WATERYEAR 1991 - EASTERN SIERRA NEVADA
MONTHLY RUNOFF (mm)
CRYSTAL
RUBY
SPULLER
LOST
0
100
200
300
400
500
MAR
APR
MAY
JUN
JUL
AUG
SEP

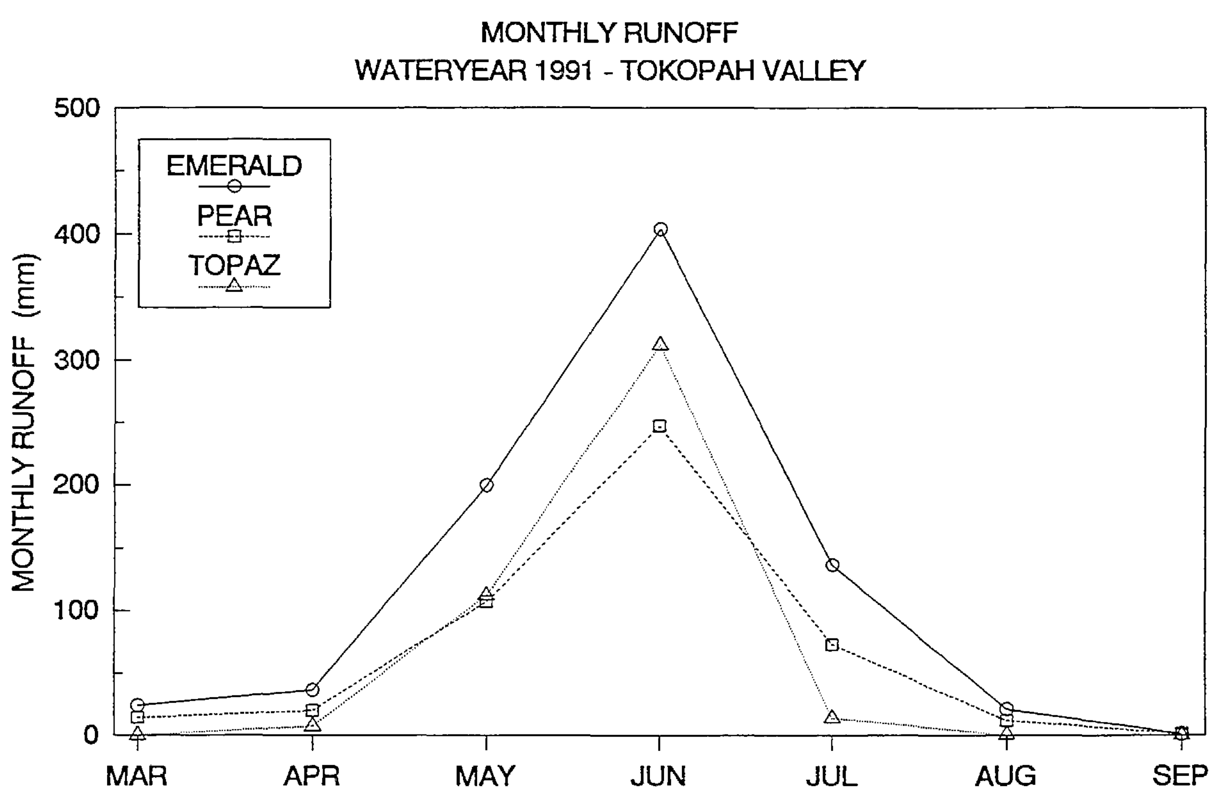
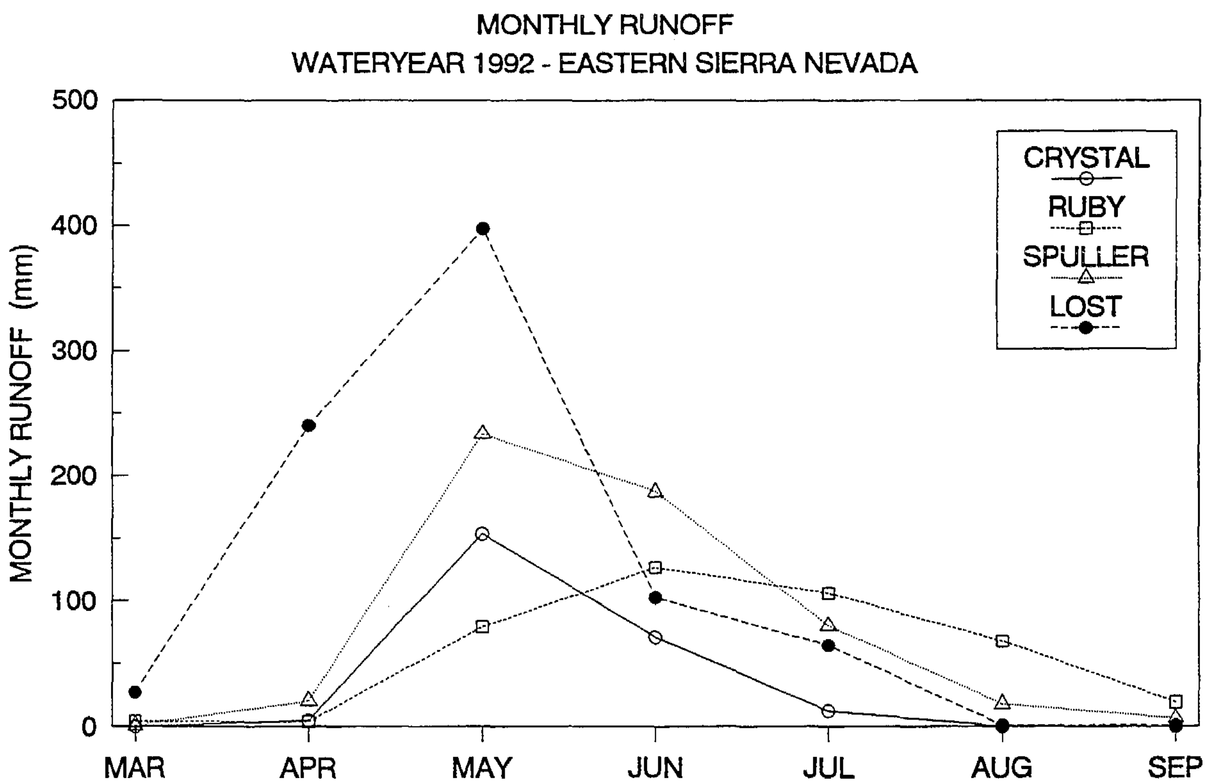
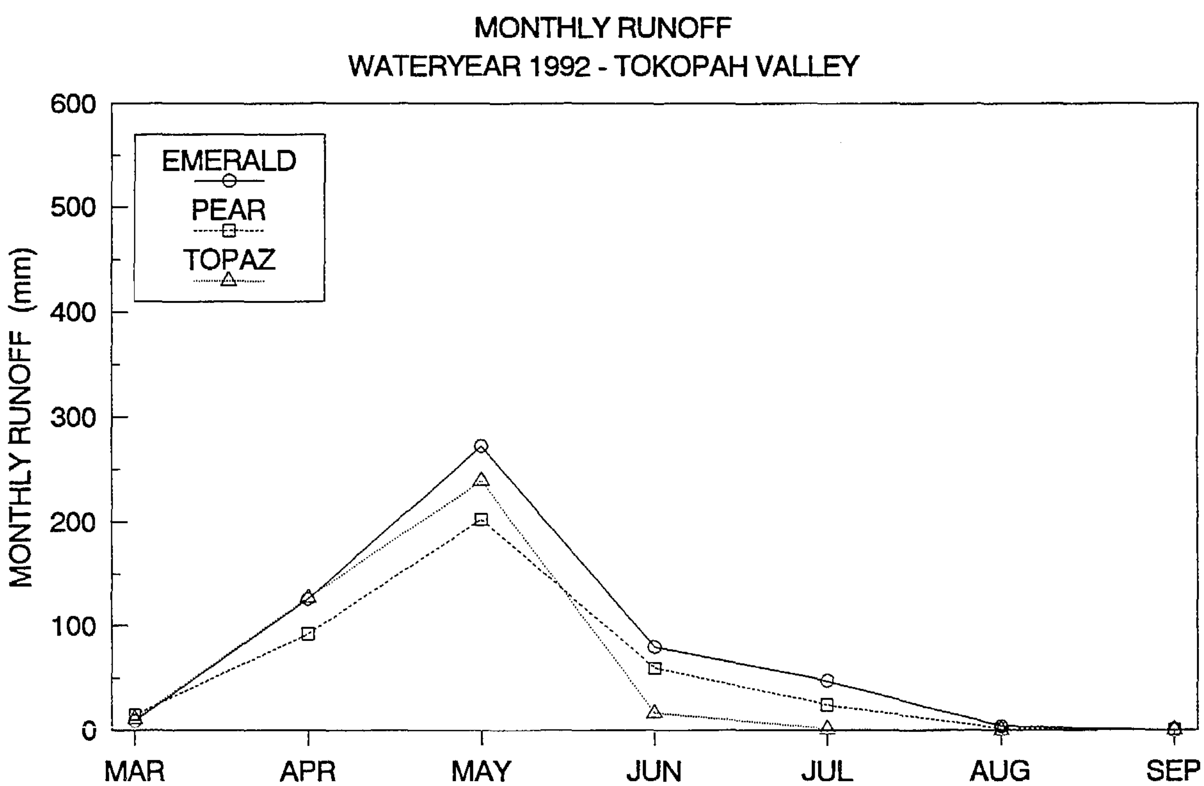

MONTHLY RUNOFF
WATERYEAR 1991 - TOKOPAH VALLEY
MONTHLY RUNOFF (mm)
EMERALD
PEAR
TOPAZ
0
100
200
300
400
500
MAR
APR
MAY
JUN
JUL
AUG
SEP

Figure II-39



MONTHLY RUNOFF
WATERYEAR 1992 - EASTERN SIERRA NEVADA
MONTHLY RUNOFF (mm)
CRYSTAL
RUBY
SPULLER
LOST
MAR
APR
MAY
JUN
JUL
AUG
SEP



MONTHLY RUNOFF
WATERYEAR 1992 - TOKOPAH VALLEY
MONTHLY RUNOFF (mm)
EMERALD
PEAR
TOPAZ
MAR
APR
MAY
JUN
JUL
AUG
SEP

Figure II-40

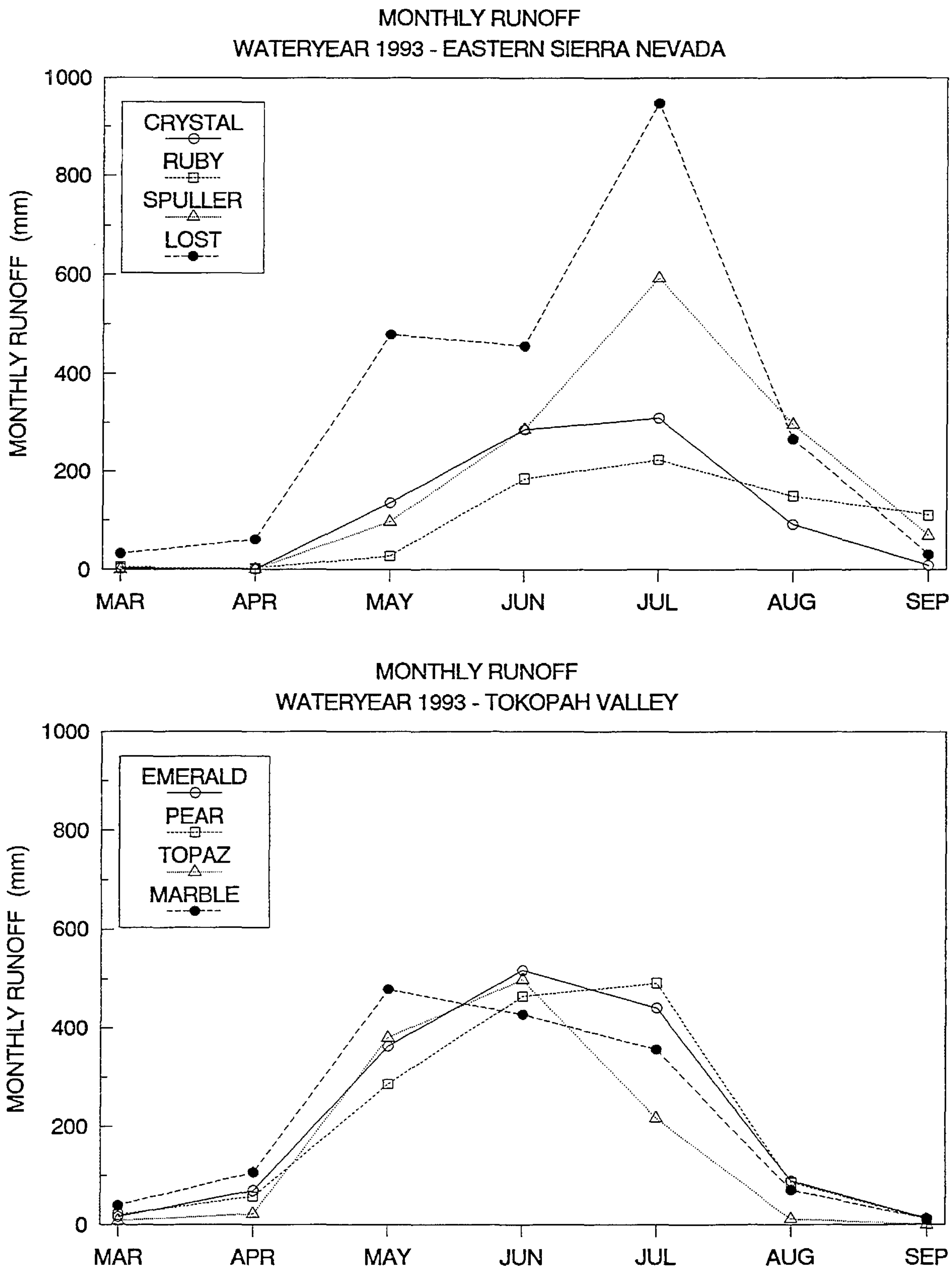

MONTHLY RUNOFF
WATERYEAR 1993 - EASTERN SIERRA NEVADA
CRYSTAL
RUBY
SPULLER
LOST
MONTHLY RUNOFF (mm)
0
200
400
600
800
1000
MAR
APR
MAY
JUN
JUL
AUG
SEP
MONTHLY RUNOFF
WATERYEAR 1993 - TOKOPAH VALLEY
EMERALD
PEAR
TOPAZ
MARBLE
MONTHLY RUNOFF (mm)
0
200
400
600
800
1000
MAR
APR
MAY
JUN
JUL
AUG
SEP

Figure II-41

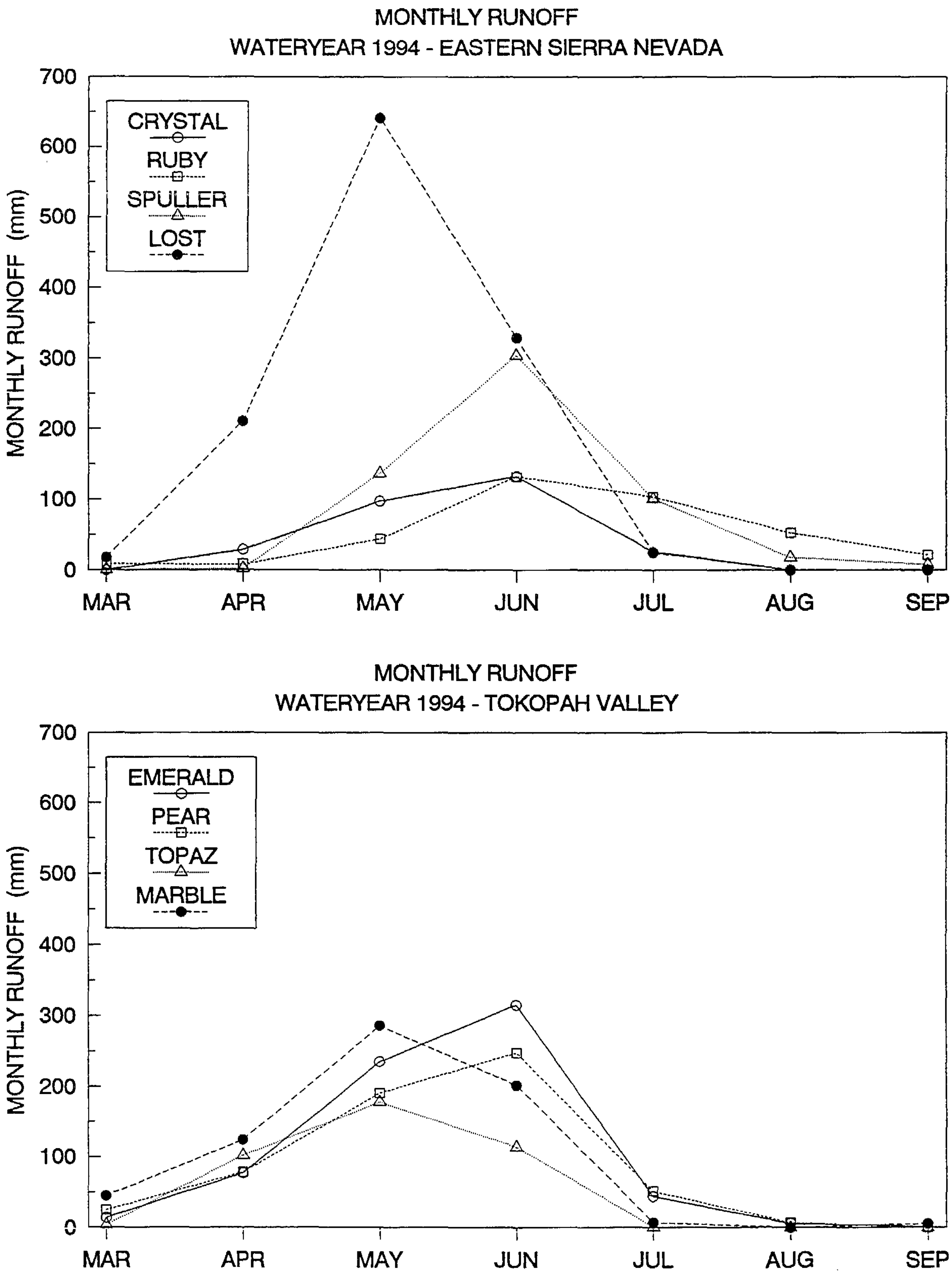
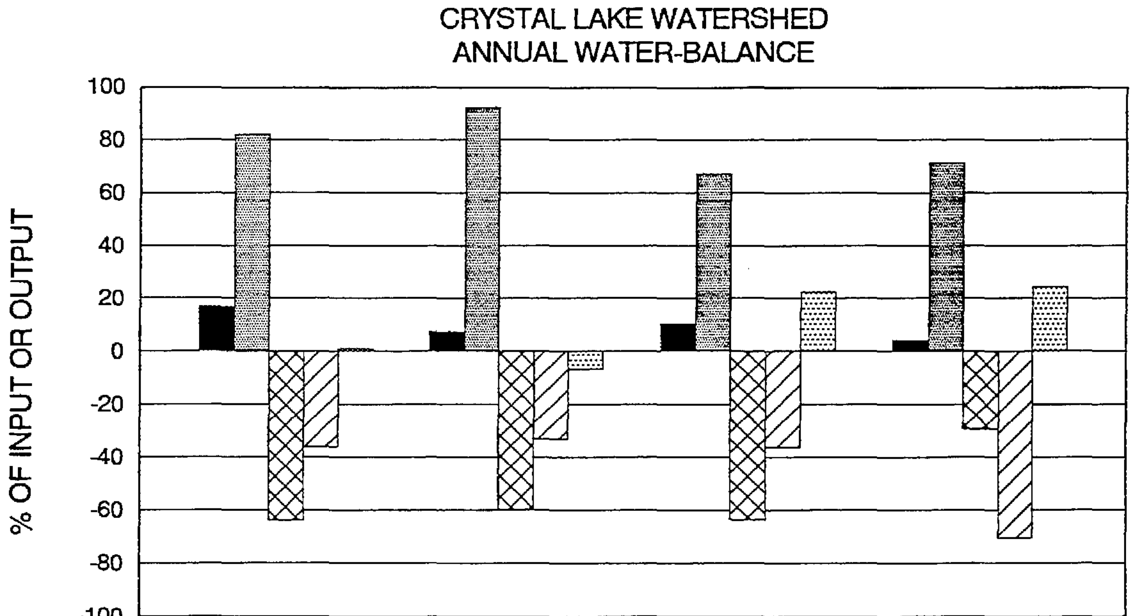

MONTHLY RUNOFF
WATERYEAR 1994 - EASTERN SIERRA NEVADA
MONTHLY RUNOFF (mm)
CRYSTAL
RUBY
SPULLER
LOST
0
100
200
300
400
500
600
700
MAR
APR
MAY
JUN
JUL
AUG
SEP
MONTHLY RUNOFF
WATERYEAR 1994 - TOKOPAH VALLEY
MONTHLY RUNOFF (mm)
EMERALD
PEAR
TOPAZ
MARBLE
0
100
200
300
400
500
600
700
MAR
APR
MAY
JUN
JUL
AUG
SEP

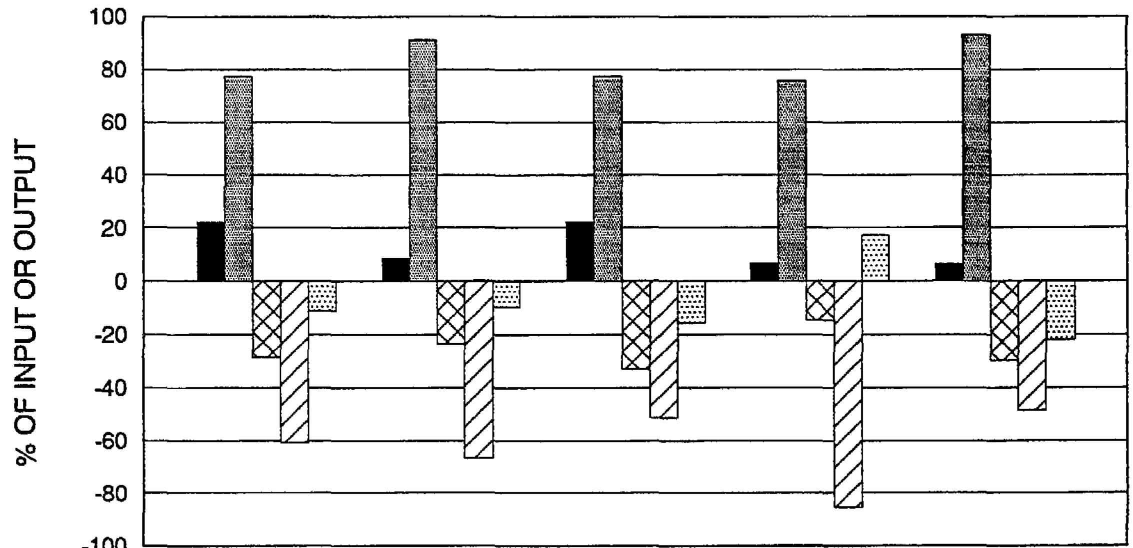
Figure II-42



units=mm	WY 1990	WY 1991	WY 1992	WY 1993
RAIN	122	63	124	104
SNOW	591	764	807	1733
EVAP.	-450	-574	-419	-368
OUTFLOW	-255	-320	-241	-881
RESIDUAL	8	-66	270	589

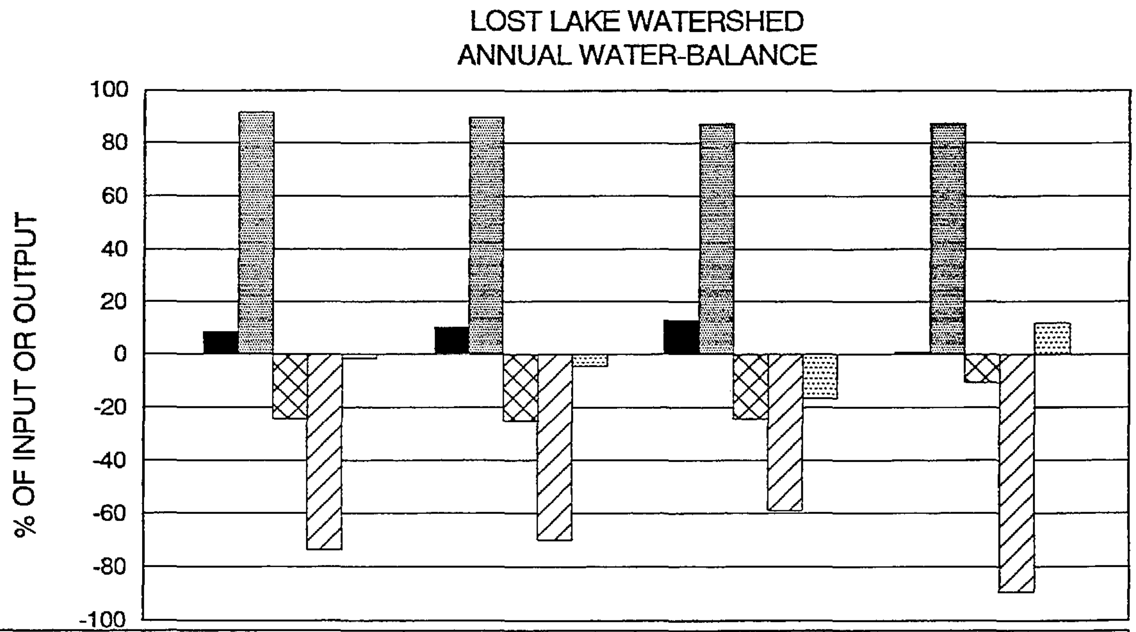
Figure II-43

EMERALD LAKE WATERSHED
ANNUAL WATER-BALANCE



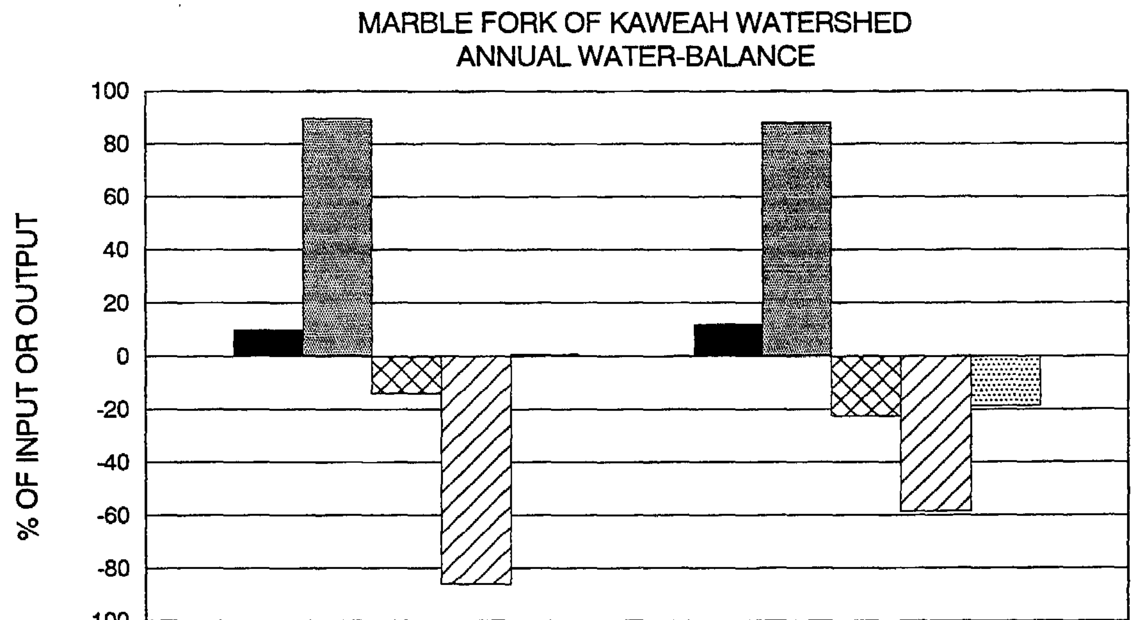
units=mm	WY 1990	WY 1991	WY 1992	WY 1993	WY 1994
RAIN	159	88	170	200	100
SNOW	568	970	617	2185	835
EVAP.	-259	-295	-366	-278	-432
OUTFLOW	-551	-832	-569	-1611	-709
RESIDUAL	-83	-69	-148	496	-217

Figure II-44



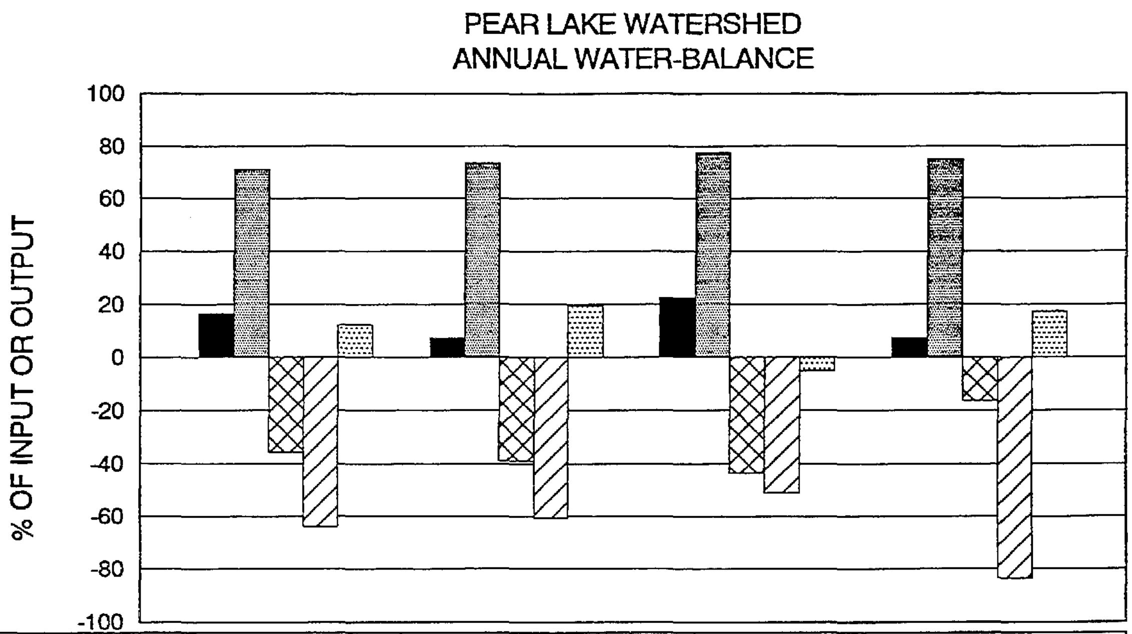
units=mm	WY 1990	WY 1991	WY 1992	WY 1993
RAIN	89	108	127	29
SNOW	933	954	874	3017
EVAP.	-259	-295	-366	-278
OUTFLOW	-780	-820	-882	-2359
RESIDUAL	-17	-54	-247	410

Figure II-45



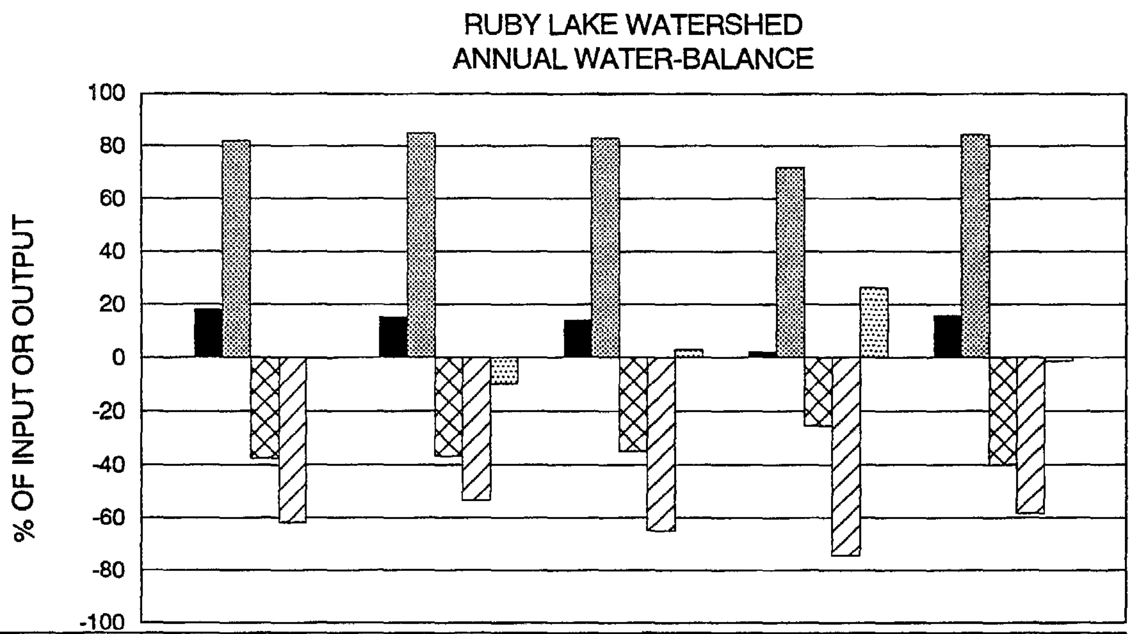
units=mm	WY 1993	WY 1994
RAIN	200	100
SNOW	1805	726
EVAP.	-278	-300
OUTFLOW	-1715	-776
RESIDUAL	12	-251

Figure II-46



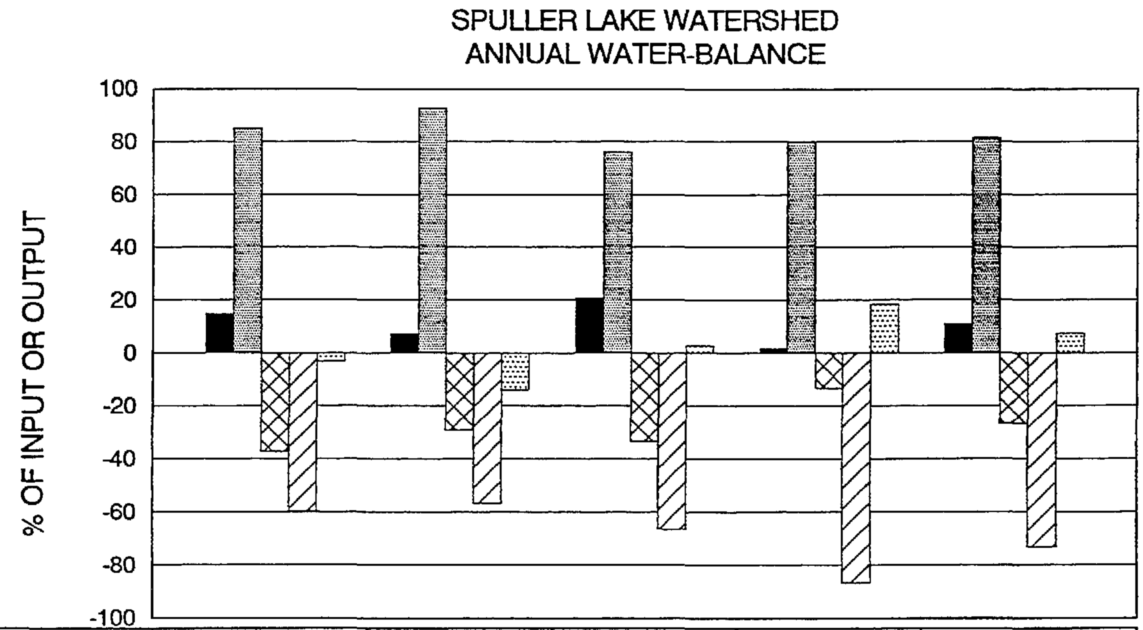
units=mm	WY 1990	WY 1991	WY 1992	WY 1993
RAIN	159	88	170	200
SNOW	681	902	583	2005
EVAP.	-259	-295	-366	-285
OUTFLOW	-464	-457	-431	-1460
RESIDUAL	118	238	-44	461

Figure II-47



units=mm	WY 1990	WY 1991	WY 1992	WY 1993	WY 1994
RAIN	136	101	102	44	113
SNOW	613	567	602	1502	613
EVAP.	-284	-306	-238	-254	-300
OUTFLOW	-467	-443	-444	-742	-437
RESIDUAL	-3	-81	22	549	-11

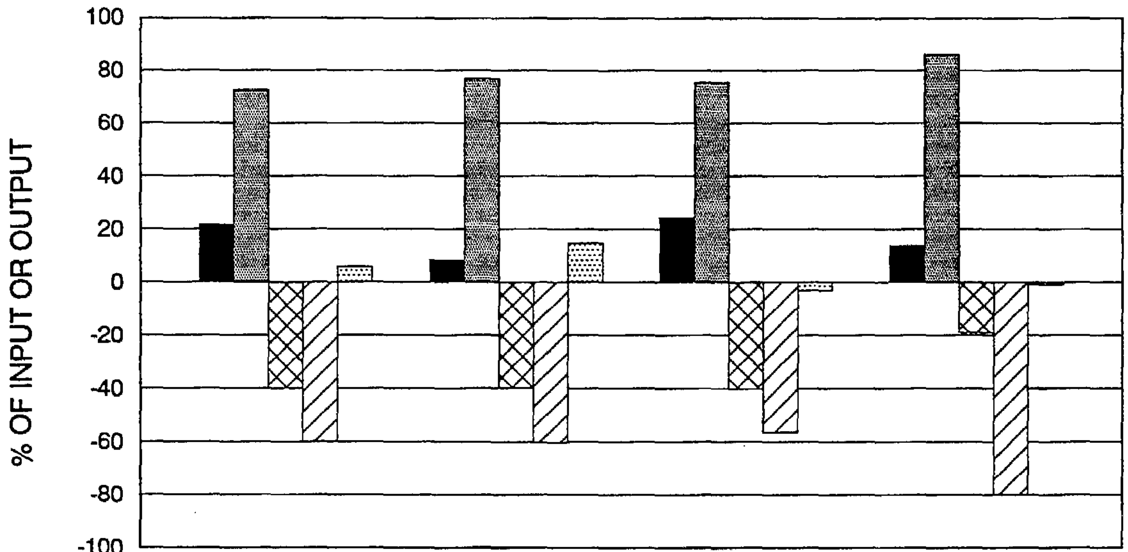
Figure II-48



units=mm	WY 1990	WY 1991	WY 1992	WY 1993	WY 1994
RAIN	129	75	190	44	118
SNOW	735	947	698	1961	873
EVAP.	-343	-413	-289	-206	-244
OUTFLOW	-549	-807	-572	-1349	-667
RESIDUAL	-28	-198	28	451	79

Figure II-49

TOPAZ LAKE WATERSHED
ANNUAL WATER-BALANCE



units=mm	WY 1990	WY 1991	WY 1992	WY 1993
RAIN	159	88	170	200
SNOW	531	807	527	1235
EVAP.	-259	-295	-300	-278
OUTFLOW	-389	-446	-420	-1171
RESIDUAL	42	155	-23	-14

Figure II-50